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Sediment characterization of North Atlantic systems, New England

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NOAA NATIONAL ESTUARINE INVENTORY:

SUPPLEMENT

SEDIMENT CHARACTERIZATION OF NORTH ATLANTIC SYSTEMS, NEW ENGLAND

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SEDIMENT CHARACTERIZATION OF NORTH ATLANTIC SYSTEMS, NEW ENGLAND

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PROJECT DESCRIPTION

NOAA's National Estuarine Inventory (NEI) is a series of related activities of the Office of Oceanography and Marine Assessment (OMA), National Oceanic and Atmospheric Administration (NOAA) that aims to develop a national estuarine data base and assessment capability. Initiated in June 1983 as part of NOAA's program of strategic assessments, the broad goal of the NEI is to build a comprehensive computerized data base for evaluating the health and status of the Nation's estuaries. It aims to bring estuaries into focus as a national resource base. Without a systematic set of data with common coordinates, units and classifications, it is difficult to analyze or compare estuaries, to assess their regional influence and to generate useful information in the form of sediment charts or desk-top computer summaries.

In May 1990 the Sediment and Contaminant Inventory (SCI) was initiated to develop a comprehensive information base on the distribution of bottom sediments and their contaminants. The SCI provides a new computer data base and it characterizes the essential and typical sedimentological features of each system. This is one step in the compilation of a regional synthesis, thus bridging the gap between site specific studies and a regional data base. The ultimate goal of the characterization is to learn the status of sediment distributions in the Nation's estuaries. It shows the most recent and mappable data that exist, where it comes from and where the gaps are that need to be filled. The data are organized into systematic data sets that are easily retrievable by personal computers. The computer will display the sediment maps together with living marine resource distributions, wetlands, pollutant sources and circulation routes to make comparisons and rankings. NOAA will ensure that the products are useful and available to coastal resource managers.

CONTENTS

EXPLANATION

Selection of Estuaries

The estuarine systems selected are from the NOAA National Estuarine Inventory in the North Atlantic region (Figure 1). The principal spatial unit of each system is the estuarine drainage area (EDA) defined in the NEI data atlas (U.S. NOAA, 1985). The sediment distributions embrace the estuarine bottom area, i.e. from the head of tides to the mouth where the estuary meets the ocean, bay or sound as determined by physiographic features (U.S. NOAA, 1985). Data coverage embraces whole estuaries and far-field distributions. Chart scales are smaller than 1:80,000 and chart units larger than 0.06 square kilometer.

Sources of Information

Data on bottom sediment characteristics and sediment distributions come from a variety of existing sources: computer files, published and unpublished literature including masters theses, doctoral dissertations and laboratory file data. The data come in many forms: e.g. tabulations, graphs and charts of distributions. Data entered into the data base and used to compile sediment charts, come from references considered primary sources whereas general information used to characterize the sediments and to interpret sedimentary processes come from references considered secondary sources.

Data Base Organization

The data were selected to provide the most up-to-date and comprehensive spatial coverage on bottom sediments. They consist of either laboratory processed data obtained from analysis of samples or cores collected at individual stations, or charted distributions copied from a published reference.

The sediment data are organized and processed into systematic data sets in digital form through a sequence of steps illustrated in Figure 2. (1) Once the data are identified and acquired, they are (2) inventoried and documented by bibliographic referencing, then (3) sorted by location, parameter and by spatial coverage, and (4) assessed for quality, i.e. completeness, consistency for compilation into chart "mosaics," (5) selected for inclusion in the data base with priority given to the best available, most recent and mappable laboratory processed data. Then, (6a) the point station data are reduced to common units, digitized in GIS (Geographic Information System) using either Arc Info or a Numonics NUM 2200 unit and then entered into a PC Quattro Pro spreadsheet. They are entered by data source, sample number, geographic coordinate, and parameter; textural distributions are classified into percent mud and the Shepard classification (Shepard, 1954), or mean and median diameter. The PC used is a NEC Powermat 3865X personal computer equipped with Map Info Map File Import/Export package. Alternately, (6b) the chart distributions are scaled to a standard NOS chart, transferred to a mylar overlay and digitized by NOAA's Arc Info unit using the GIS and a plotting package. The digitized data are then (7) plotted as "test" charts that serve to validate data in the data base. The resulting distributions from steps 6b and 7 are then examined for consistency, verified and (8) stored in a computer file. (9) The file data are processed by making digital contour plots for the desk-top atlas and (10) the output verified and reassessed for quality.

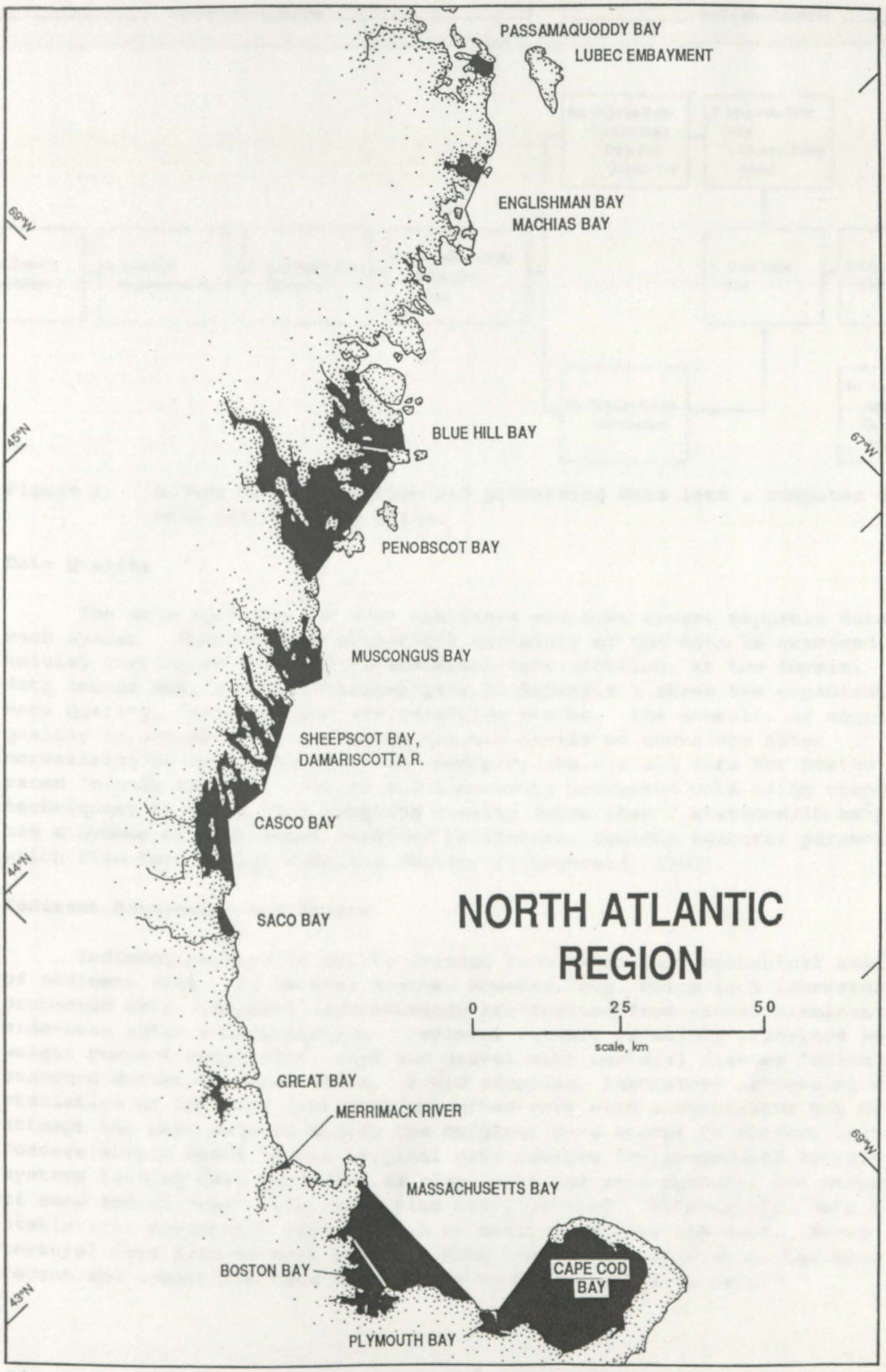


Figure 1. Location of estuarine systems characterized and included in the NEI data base for the North Atlantic-New England region. Estuarine drainage areas, bold line.

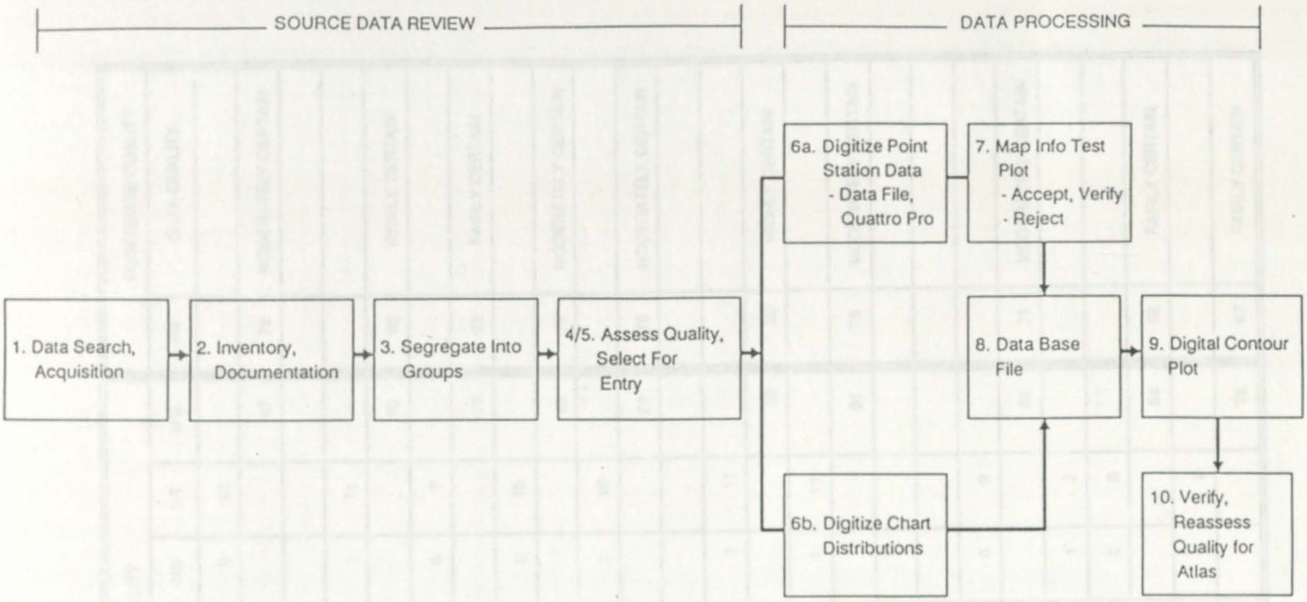


Figure 2. Scheme of organization and processing data into a computer data base and desk-top atlas.

Data Quality

The data used are the best available and most recent mappable data for each system. The relative scientific certainty of the data is assessed, after initial sorting of source data and after test plotting, at two levels: (1) by data source and (2) their "mappability." Appendix 1 shows the organization of data quality, criteria used and weighting scales. The overall, or aggregate, quality is estimated by averaging the two levels of certainty after normalizing to 100 (Table 1). For example, the overall data for Boston Bay is rated "highly certain." It is all laboratory processed data using standard techniques; it has a high sampling density (more than 7 stations/10 km^2) and has a number of additional measured parameters, besides textural parameters, which also have a high sampling density (Fitzgerald, 1980).

Sediment Parameters and Charts

Sediment texture is mainly derived from laboratory mechanical analyses of sediment size. In several systems however, e.g. which lack laboratory processed data, sediment distributions are derived from visual examination or side-scan sonar interpretation. Sediment texture is mainly expressed as weight percent clay, silt, sand and gravel with textural classes following the standard Wentworth grade scale. Field sampling, laboratory processing and statistics of the size distributions often vary with investigator but no attempt has been made to modify the original data except to convert units. Readers should refer to the original data sources for procedural details. For systems lacking data expressed as clay, silt and sand percent, the percentage of sand and of "mud" (i.e. silt plus clay) is used. Alternately, data for the statistical parameters mean, median or modal diameters are used. Where textural data from several reliable data sources are available, the most recent and compatible data are used to compile a chart "mosaic."

Table 1. Data Quality Weightings by Source and by Mappability

NEI SYSTEM	ID	S1	S2	S3	S4	SS	ST	SQ	M1	M2	M3	M4	MS	MT	MQ	AQ	DATA QUALITY
	DATA SOURCE QUALITY								MAPPABILITY							AGGREGATE QUALITY	
Cape Cod Bay	1	3	2	2	5	1	13		3	3	3	1	0	10			
	2	3	1	3	2	1	10								67	72	MODERATELY CERTAIN
	AVERAGE							77									
Boston Bay	1	3	2	3	5	1	15		3	2	3	2	1	11			
								100							92	96	HIGHLY CERTAIN
Massachusetts Bay	1	3	2	2	2	1	10		1	2	3	1	0	7			
								66							58	62	FAIRLY CERTAIN
Merrimack R.	1	3	1	2	5	0	11		3	3	3	1	0	10			
								73							83	78	MODERATELY CERTAIN
Great Bay	1	3	2	3	5	1	14		3	2	3	1	1	10			
	2	3	2	3	2	1	11								67	75	MODERATELY CERTAIN
	AVERAGE							83									
Saco Bay	1	3	2	2	5	1	13		3	3	3	1	1	11			
								87							92	90	HIGHLY CERTAIN
Casco Bay	1	3	2	2	1	1	9		2	3	2	3	1	11			
	2	3	1	3	1	1	9								91	75	MODERATELY CERTAIN
	AVERAGE							60									
Sheepscoot Bay/	1	3	2	2	1	1	9										
Damariscotta R.	2	3	2	2	5	1	13		3	2	3	1	0	9			
	AVERAGE							73							69	71	MODERATELY CERTAIN
Penobscot Bay	1	3	1	3	1	1	9		1	2	2	1	1	7			
	2	3	2	2	2	1	10		1	2	2	1	0	6			
	AVERAGE							63							54	58	FAIRLY CERTAIN
Muscongus Bay	1	3	2	2	2	0	9		1	3	3	1	1	9			
								60							75	67	FAIRLY CERTAIN

	DATA SOURCE QUALITY								MAPPABILITY							AGGREGATE QUALITY	
NEI SYSTEM	ID	S1	S2	S3	S4	SS	ST	SQ	M1	M2	M3	M4	MS	MT	MQ	AQ	DATA QUALITY
Blue Hill Bay	1	3	2	2	1	1	9		1	1	3	1	1	7			
								60							58	59	FAIRLY CERTAIN
Englishman Bay/	1	2	0	2	0	0	5		0	1	1	1	0	3			
Machias Bay	2	2	0	2	0	0	5										
	AVERAGE							33							25	29	DOUBTFUL
Passamaquoddy/	1	2	1	2	5	0	10		3	3	3	1	0	11			
Lubec Embayment								66							73	70	MODERATELY CERTAIN

DATA SOURCE QUALITY
ID: SOURCE ID
S1: DATA FORM
S2: DEGREE OF LAB PROCESSING
S3: DOCUMENTATION
S4: SAMPLING DENSITY
SS: ADDITIONAL PARAMETERS
ST: SUM OF THE WEIGHTINGS
SQ: NORMALIZED WEIGHTING

MAPPABILITY
M1: SAMPLING DENSITY
M2: SPATIAL COVERAGE
M3: CONSISTENCY
M4: TEMPORAL COVERAGE
MS: ADDITIONAL PARAMETERS
MT: SUM OF THE WEIGHTINGS
MQ: NORMALIZED WEIGHTING

AGGREGATE QUALITY

AQ (SCALE)	DATA QUALITY
Over 85	HIGHLY CERTAIN
70 - 85	MODERATELY CERTAIN
55 - 70	FAIRLY CERTAIN
40 - 55	REASONABLE INFERENCE
Below 40	DOUBTFUL

Total carbon (carbonate plus organic carbon) is usually measured by high temperature combustion in an induction furnace. Organic carbon may also be measured by high combustion after removal of carbonate by acid digestion). Organic matter is usually found by weight loss after oxidation such as treatment with hydrogen peroxide or weight loss on ignition. Since organic carbon represents about half of the total organic matter, organic matter percentages are also derived by multiplying organic carbon values of the original data by a factor of 1.8 following Bader (1954, 1955). Sediment organic carbon and/or organic matter are linearly related to the nitrogen content with ratios of about 11 to 13 (Bader, 1955). These parameters therefore, are an indication of eutrophic substances.

Short-term rates of sedimentation spanning decades (< 150 years B.P.) are determined from either bathymetric changes or geochronology. Bathymetric changes are measurements of shoaling or deepening of the bottom between successive depth surveys (Shepard, 1953). These changes reveal spatial patterns of sedimentation rate but are usually not as precise as radiometric measurements of sediment age with depth in sediment cores, e.g. ^{210}Pb and ^{137}Cs. The ^{210}Pb measurements reveal temporal variations with depth and are sensitive to local variations. Where most sediment accumulates in dredged channels, maintenance dredging records of depth changes also provide useful data.

Contamination Status

The relative status of pollution is partly characterized by the system's susceptibility to pollution, i.e. the potential for pollution as determined by hydraulic characteristics and by the exposure to anthropogenic activities in the watershed. Following Biggs *et al.* (1989) the susceptibility characteristics are:

1. <u>Hydraulic Character - HL</u>

   Hydraulic loading which is the contaminant handling capacity of a system based on the volume and flushing. It includes both freshwater and tidal flushing and indicates how well an estuary can dilute or transport contaminants. When hydraulic loading is low flushing is sluggish and the estuary tends to retain contaminants.

2. <u>Stratification - STRAT</u>

   Estuaries with strong vertical salinity gradients are likely to develop hypoxia or anoxia and to recycle nutrients more efficiently than homogeneous systems.

3. <u>Population/Estuary Surface Area - P/EA</u>

   This ratio expresses the estuary loads of anthropogenic substances likely to result from watershed activity particularly point sources. When P/EA is high, nutrient loads to the estuary may be high.

4. Agriculture Workers/Estuary Surface Area - AG/EA

This ratio expresses the estuary loads of anthropogenic substances likely to result from watershed activity particularly non-point sources. When AG/EA is high, nutrient and toxic loads to the estuary may be high.

5. Chemical Workers + Population and Estuary Area - C + P/EA

This relation expresses the estuary loads of anthropogenic substances likely to result from watershed activity, particularly point sources. When these values are high, toxic loads to the estuary may be high.

The parameters "3," "4," and "5" are ratios of the anthropogenic watershed activity to the hydraulic loading, parameter "1". They express the concentrations of pollutants that could result considering the given load to the system and the systems ability to flush that load to sea. The relative ranking, high, medium and low, in the characterization summaries is based on comparison of 78 U.S. estuaries from the National Estuarine Inventory (Biggs *et al.*, 1989).

SEDIMENT CHARACTERIZATION

N130 CAPE COD BAY AND PLYMOUTH BAY

Description

Cape Cod Bay is a large deep embayment lying inside the arm of Cape Cod which provides partial protection from open ocean swell (Figure 1A). Configuration and bathymetry are shaped by glacial action (Hough, 1942). The eastern and western shores consist of glacial interlobate moraines and outwash while the south shore consists of a terminal moraine, mainly outwash deposits. The bottom configuration is shaped by glacial deposition on an erosional surface of low relief. Subsequent sediment reworking during the Holocene transgression in the last 7,000 years, besides shore erosion and spit accretion have smoothed the configuration. Marsh accretion has filled local stream valleys. The Bay is relatively free of dredging and dumping except for disposal off Plymouth Bay and the Cape Cod Canal entrance and in Wellfleet Harbor.

The modern Bay is relatively young forming less than 10,000 years ago. It formed when the most recent rise of sea level inundated former glacial deposits (Nilsson, 1973). The Provincetown spit began to form about 5,500 to 6,000 years ago extending the northeast Bay shore. Submergence in the last 2,000 years is about 1.0 mm/yr (Gornitz and Lebedeff, 1987) while the short-term rate is 1.9 mm/yr (Emery and Aubrey, 1991).

Sediment Sources

Sources are poorly known but fluvial input of fine sediment is likely very low because the drainage basin area is small, 2,070 km^2, discharge is low and drainage poorly developed. Most streams flow into small estuaries or reentrants rather than directly into the Bay (Hough, 1942). In contrast, much silt and clay in deeper parts likely comes from marine areas as well as erosion of shore bluffs composed of glacial fill. Additionally, reworking of relic glacial deposits on the Bay floor by storm waves, such as the northeast trending ridge of recessional moraine in the central Bay, likely supplies some fine material while benthic production on the Bay floor supplies shell. Shore erosion supplies sand especially along the southwest Bay shore. Much sand comes from erosion of the ocean coast via littoral drift around Race Point and Provincetown (Fisher, 1987).

Pathways

Sediment transport is driven mainly by tidal currents which are modified in speed and direction by the wind. Near-bottom current speed generally decreases inward (southward and westward) from Race Point, i.e. from about 20 cm/s to < 6 cm/s near Cape Cod Canal (Signell and Jenter, 1992). Since mean near-bottom flow is directed westward and southward from Race Point (Butman and Signell, 1992), fine sediment is likely transported into the Bay from marine areas. Consequently, the central Bay floor is a major sink for silt and clay. Additionally, benthic organisms encourage deposition by pelletizing filtered sediment.

Near-surface mean flow is broadly organized into a counterclockwise spin (Bumpus, 1974). Prevailing southeast winds combined with tidal currents drive water seaward and northeasterly north of Race Point, which is the main exit pathway (Butman and Signell, 1992). This water is replaced by a southerly flow along the southwest side. The pattern however, can reverse in the fall season (Butman and Signell, 1992). There is a pronounced longshore drift of sand westward along Race Point and southwestward along the tip of Cape Cod (Fisher, 1987).

Waves generated by northeasterly storms erode the western shore and resuspend or remove fine sediment at considerable depth (to 24 m) (Hough, 1942), producing gravel zones. Fine sediment likely moves toward deep water in the central Bay and accumulates after undergoing many cycles of settling, deposition and resuspension. Small amounts however, escape to the ocean north of Race Point.

Sinks

The main sink of mud accumulation is the central Bay. Additionally, mud accumulates in protected nearshore embayments, tidal lagoons, flats and marshes. Short-term sedimentation rates in Barnstable Harbor range 3 to 8 mm/yr and average 5.5 mm/yr (Redfield, 1972). Shepard and Wanless (1971) show that Plymouth Harbor has shoaled since 1765.

Bottom Sediments

Coarse sand and gravel with median diameters greater than 0.5 mm ($< 1\ \phi$) is abundant along margins of the Bay, i.e. less than 12 m deep on the south side and less than 24 m on the east side (Figure 1A) (Hough, 1942). At greater depths seaward, this type gives way to fine and medium sand, 0.06 to 0.50 mm ($1 - 4\ \phi$) median size, and farther seaward in the central Bay, this grades to silt and clay ($< 4\ \phi$) (Figure 1A). The coarser material has the highest sorting while the fine sediments are more poorly sorted (Hough, 1942). Locally, gravel zones, possibly relic glacial deposits, are found on topographic highs of the central Bay. Shell layers 1 to 2 cm thick also occur in deep mud zones. Organic carbon content throughout the Bay ranges 0.1% to 1.5% being highest in the central Bay mud zone (Hathaway, 1971).

Sediments of Plymouth Harbor and Duxbury Bay are dominantly sand. Sand greater than 60% covers shoals and in tidal channels of the central Bay (Figure 1B). Mud greater than 40% is restricted to inner reentrants and reflects inward diminished tidal energy.

Contamination Status

In terms of pollution susceptibility among the nation's estuaries, Cape Cod Bay has a high efficiency for trapping particles (U.S. NOAA, 1990) because of its relatively deep retentive basin. It has a moderate susceptibility to dissolved toxics and nutrients (U.S. NOAA, 1990) because of its moderate tidal flushing ability and small drainage basin size relative to Bay area volume. Although fluvial input is very low, the Bay is affected by far-field contamination from Boston Harbor (Cahill and Imbalzano, 1991). Most near-field contaminants however, are likely retained in marginal harbors and reentrants.

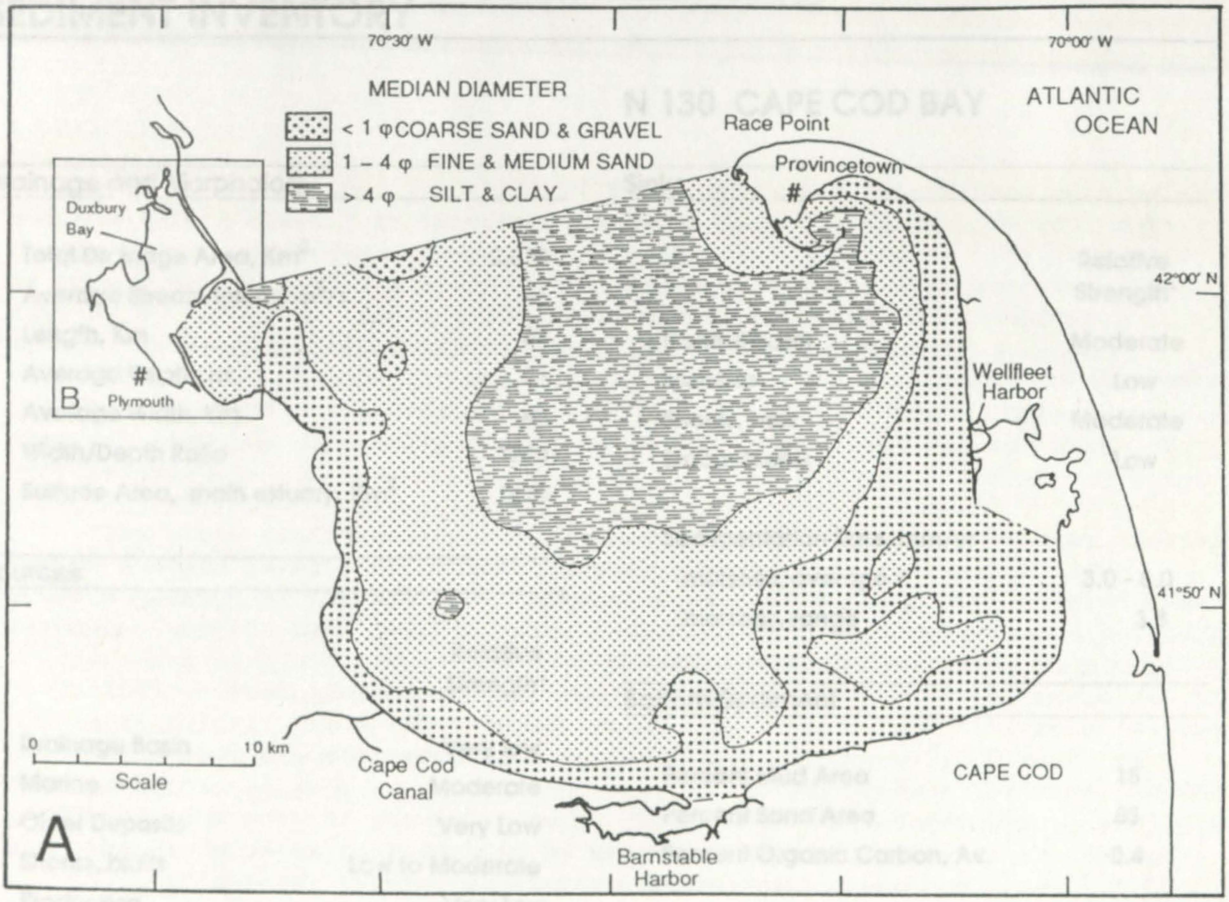
Bottom Sediment Charts

The bottom sediments of Cape Cod Bay (Figures 1A, 1B) have been charted from bottom samples collected at 135 stations by Hough (1942). Stations were located on lines crossing the Bay in various directions between buoys and lighthouses. Sampling intervals were about one mile along the lines. Positioning was by ranging and water depth. A Trask coring tube was used in fine sediment while a clamshell snapper grab was used for coarser material (Hough, 1942).

The distribution of median grain size diameter is classified as presented by the original author, Hough (1942) based on Wentworth classification. The chart was prepared by computer mapping Hough's numeric data using a minimum mappable unit of 0.6 km^2. The major boundaries are essentially the same as those charted by Hough (1942). Additionally, seven stations were occupied by U.S.G.S. for samples analyzed for organic carbon from a computer file provided by J. Hathaway (personal communication).

The distribution of mud percentage in Plymouth Harbor and Duxbury Bay (Figure 1B) was mapped by computer from file data provided by the U.S. Geological Survey, Woods Hole, Massachusetts, J. Hathaway (personal communication). It is based on 277 samples collected by grab and by hand in 1987. Data are classified based on percent weight of gravel, sand, silt and clay.

For sources of information and explanation of data in the sediment inventory sheet, see text and Appendix 2.



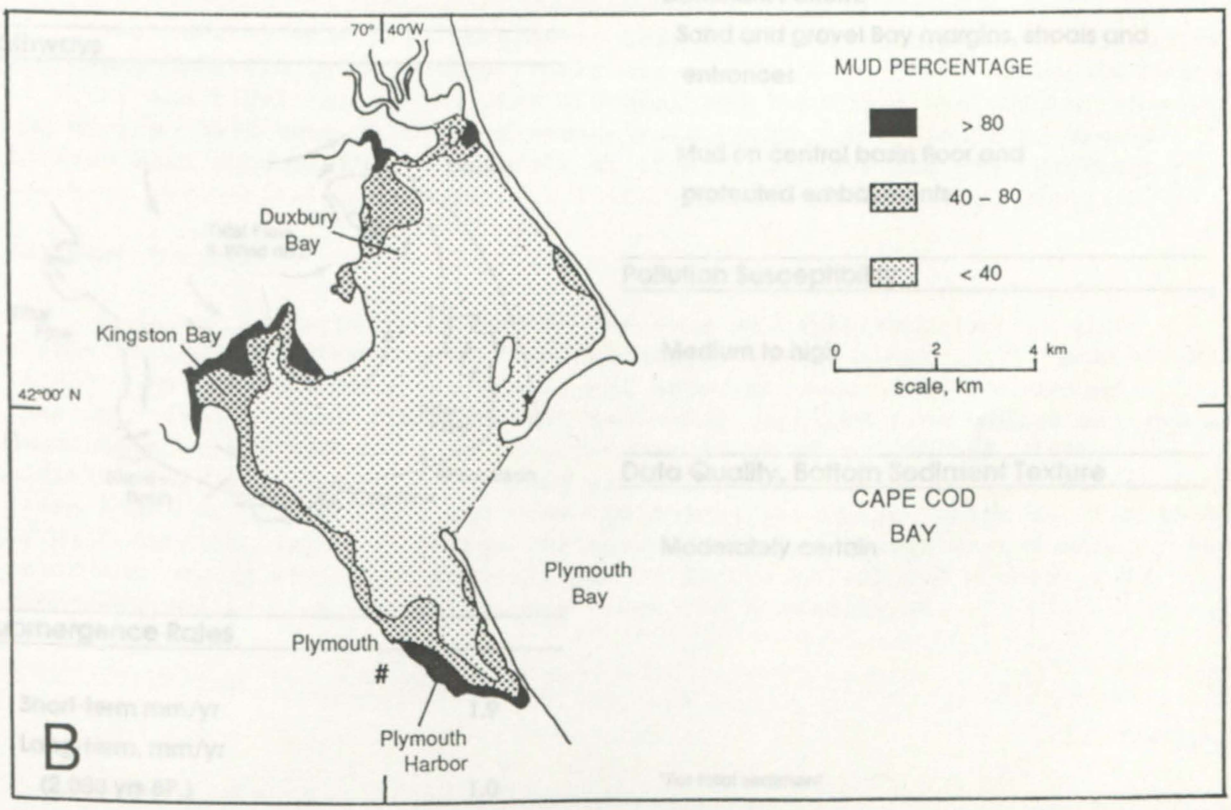


Figure 1A. Distribution of median diameter in Cape Cod Bay from data of Hough (1942).

Figure 1B. Distribution of mud percentage in Plymouth Bay from file data of U.S. Geological Survey (1989).

SEDIMENT INVENTORY

N 130 CAPE COD BAY

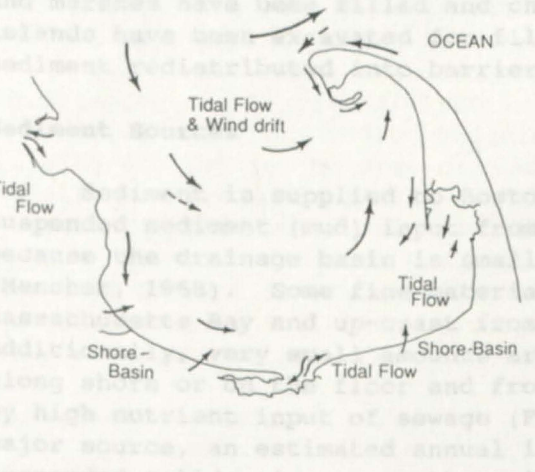
Drainage and Morphology

Total Drainage Area, Km^2	2,070
Average Stream Inflow, m^3/s	51
Length, Km	37
Average Depth, m	23
Average Width, Km	40
Width/Depth Ratio	1740
Surface Area, main estuary, Km^2	1420

Sources

	Relative Strength*
Drainage Basin	Very low
Marine	Moderate
Older Deposits	Very Low
Shores, bluffs	Low to Moderate
Production	Very Low

Pathways



Submergence Rates

Short-term mm/yr	1.9
Long-term, mm/yr (2,000 yrs BP.)	1.0

Sinks

	Relative Strength*
Central Basin	Moderate
Marshes	Low
Shoals, bars	Moderate
Embayments	Low

Sedimentation Rate, mm/yr

marshes, average	3.0 - 8.0
marshes, range	3.8

Bottom Sediment

Percent Mud Area	15
Percent Sand Area	85
Percent Organic Carbon, Av.	0.4

Dominant Pattern:

Sand and gravel Bay margins, shoals and entrances

Mud on central basin floor and protected embayments.

Pollution Susceptibility

Medium to high

Data Quality, Bottom Sediment Texture

Moderately certain

*For total sediment

SEDIMENT CHARACTERIZATION

N120a BOSTON BAY

Description

Boston Bay (Harbor) is the most prominent urban estuary and port on the North Atlantic coast. It is a heterogeneous harbor with diverse sedimentary environments, low stream discharge and high human influence. Its bathymetry is very irregular and its hydrodynamic and sedimentation patterns have been altered by dredging, landfill and human waste input including municipal sewage, industrial discharges and shipping wastes. Two major shipping channels are cut through the Bay to 9 and 12 m depths, Nantasket Roads Channel in the south sector and President Roads Channel in the north. Open water disposal areas occur locally southeast of Peddocks Island and northwest of Deer Island.

The shore configuration and bathymetry were initially shaped by glacial action and sea level fluctuations (Knebel, 1993). Pleistocene glaciers scoured bedrock of the Bay floor several times and subsequently covered the irregular surface with glacial drift including till with cobbles and boulders, plus outwash sand and gravel and glacio-marine muds (Kaye, 1982, Oldale and Bick, 1987). Post-glacial crustal rebound caused the Bay floor to emerge, and sea level to fall -22 m about 10,000 years ago. Since that time relative sea level has risen rapidly reaching a near-still stand about 3,000 years ago. This position, as well as the subsequent rise to its present position, which proceeded at a rate of about 1.5 mm/yr (Gornitz and Lebedeff, 1987), subjected the glacial deposits to reworking by waves and currents similar to that at present (Fitzgerald, 1980). Short-term submergence rates are about 2.6 to 2.9 mm/yr (Emery and Aubrey, 1991).

When Boston was first settled in 1630 the inner harbor had an irregular shoreline indented by tributary creeks and marshland. Today, after 360 years of river and tidal deposition plus dredging and landfill, the creeks, shoals and marshes have been filled and channels narrowed. Additionally, drumlin islands have been excavated for fill or eroded by waves and the resultant sediment redistributed into barrier spits (Shepard and Wanless, 1971).

Sediment Sources

Sediment is supplied to Boston Bay from multiple sources. Fine suspended sediment (mud) input from streams is small, about 15,000 m tons/yr, because the drainage basin is small, and major streams have been dammed (Mencher, 1968). Some fine material is likely supplied from marine sources in Massachusetts Bay and up-coast from the Merrimack River (Knebel, 1993). Additionally, very small amounts are supplied from erosion of glacial deposits along shore or on the floor and from biological production which is stimulated by high nutrient input of sewage (Fitzgerald, 1980). Human wastes make up the major source, an estimated annual input of 90,000 to 105,000 m tons/yr of suspended solids, i.e. more than six times the stream input.

Pathways

Fine sediment is transported by tidal currents augmented intermittently by wind drift (Signell and Jenter, 1992). The main circulation is consistent with the pattern in a well-mixed estuary; i.e. generally counterclockwise with water entering President Roads, flowing landward and southward between islands and then leaving seaward through Nantasket Roads (Fitzgerald, 1980).

Near-bottom currents are fastest (> 50 cm/s) in constricted entrance channels and depressions; they are slowest (< 10 cm/s) over shoals of inner reaches (Knebel, 1993). Maximum near-bottom tidal current speeds diminish landward from about 80 cm/s in the entrance to 20 cm/s over inner shoals (Knebel *et al.*, 1991). Because of storm winds blowing from the north and east across outer reaches and in Massachusetts Bay, waves are strong enough to resuspend and winnow bottom sediments throughout outer parts of Boston Bay (Fitzgerald, 1980; Bothner and Butman, 1988). Resuspension is most vigorous in winter when wave activity combines with strong ebb currents.

Sinks

The main sink of mud accumulation is the inner sector of the Bay, i.e. in Quincy Bay and Dorchester Bay extending seaward to Long Island. This is a broad sheltered area between islands and headlands which includes some bathymetric lows (Fitzgerald, 1980). It is a less energetic area away from the main tidal channels where currents are less than 26 cm/s (NOS, 1977). Sedimentation rates in this area range 1.3 to 3.2 mm/yr (Fitzgerald, 1980). The mud is likely redistributed mud from Massachusetts Bay plus organic material of local origin. Additionally, fine sediments accumulate in sheltered shoal areas of Hull Bay and behind Deer Island where rates are about 2.4 mm/yr (Fitzgerald, 1980). Fastest rates of sedimentation, 4.0 mm/yr, occur in the Inner Harbor due to input of storm sewer overflows.

Bottom Sediments

Mud (> 80%) is most abundant in the Quincy Bay sink (Figure 2A). Additionally, patches occur landward of Deer Island, south of Peddocks Island and in Hull Bay. These are mainly non-dredged depositional zones of weak tidal currents (Fitzgerald, 1980). The muds are rich in silt and lean in clay (< 35%) (Fitzgerald, 1980). Organic carbon content is generally greater (ranging 4 - 5%) in the clay rich mud zones than elsewhere except near sewage outfalls as west of Deer Island. In sandy and gravelly sediments, which prevail near the harbor entrance, in erosional zones around island margins, dredged channels and south and western shores of the Bay, organic content is generally below 0.5% (Fitzgerald, 1980). Between mud and sand zones sediments are heterogeneous including mixtures of reworked glacial drift, silty sand, sandy silt, clayey silt and sand-silt-clay (Figure 2B).

Contamination Status

Boston Bay is among the least susceptible systems among the nation's estuaries (Biggs *et al.*, 1989). Despite its high population activity the hydraulic loading is low and particle trapping is intermediate. Whereas until the present, sewage wastes have been discharged from at least five treatment facilities near the north and south entrances to the Bay, besides storm water and sewage outlets discharged along the western shore and inner harbor, in about 1995 most Boston discharges will be released from an outfall in Massachusetts Bay, 15 km seaward (northeast) of Boston Bay entrance (Butman *et al.*, 1992).

Bottom Sediment Charts

The bottom sediments of Boston Bay (Figures 2A, 2B) have been charted from bottom samples collected at 160 stations. Most data come from a computer file of Hathaway (U.S. Geological Survey, 1989) which includes data of Mencher *et al.* (1968) and Fitzgerald (1980). Navigational positioning of U.S.G.S. was accomplished by Loran C (Knebel *et al.*, 1991). Stations of Mencher *et al.* (1968) were located along lines, and along channels, about 0.75 km apart. Most samples were collected by grabs or cores (Mencher *et al.*, 1968; Fitzgerald, 1980).

The distribution of mud abundance (Figure 2A) is classified into three groups and mapped by computer. This classification displays major patterns for recognizing dominant features. The chartlet, together with textural patterns (Figure 2B), was compiled using a minimum mappable unit of 0.25 km^2. Narrow transition zones of texture are not represented. Greater detail can be acquired by mapping the original data at larger scales and smaller mud class intervals.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

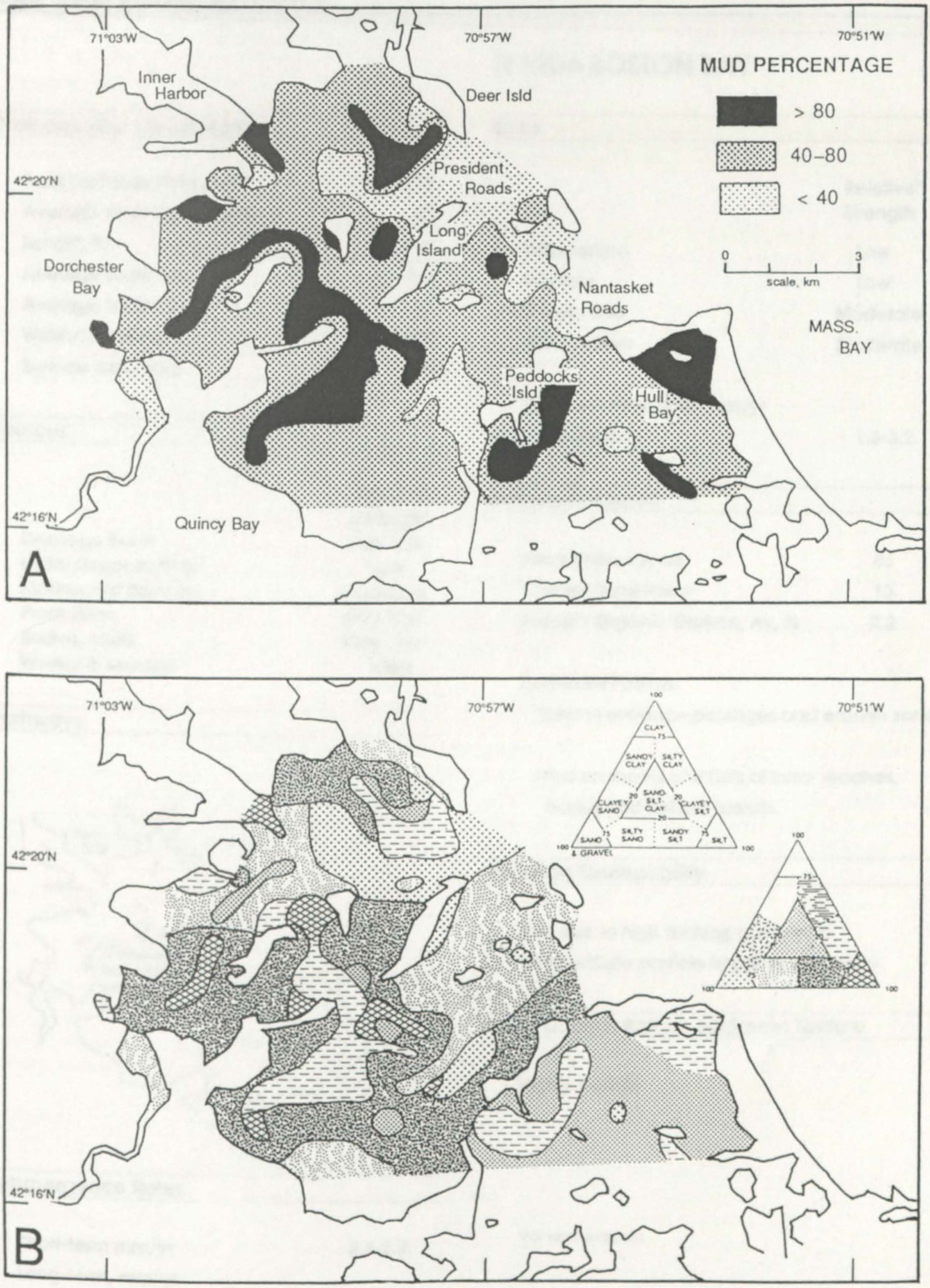


Figure 2A. Distribution of mud abundance mapped by computer, from U.S.G.S. (1989) data file and Hathaway (1971).

Figure 2B. Distribution of textural types follows the Shepard classification from same sources as Figure 2A.

SEDIMENT INVENTORY

N 120a BOSTON BAY

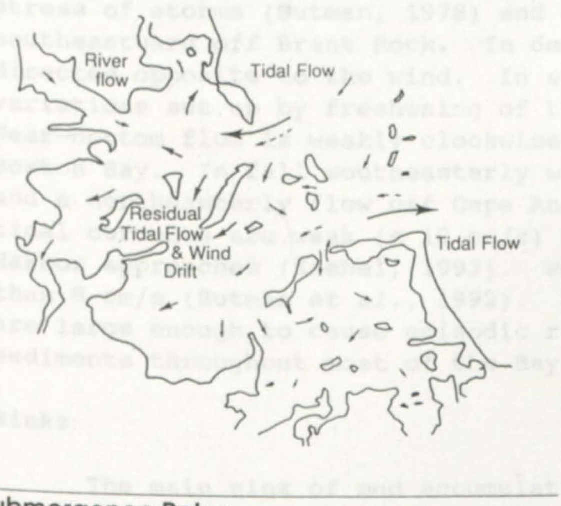
Drainage and Morphology

Total Drainage Area, Km^2	1,813
Average River Inflow, m^3/s	51
Length, Km	19
Average Depth, m	8.0
Average Width, Km	11
Width/Depth Ratio	1375
Surface Area, Km^2	179

Sources

	Relative Strength*
Drainage Basin	Very low
Older deposits, floor	Low
Marine, old deposits	Moderate
Production	Very Low
Shores, bluffs	Very Low
Wastes & sewage	High

Pathways



Submergence Rates

Short-term mm/yr	2.6-2.9
Long-term, mm/yr	
(0-3,000 yrs BP.)	1.5

Sinks

	Relative* Strength
Depressions	Low
Marshes	Low
Shoals, flats	Moderate
Inner Harbor	Moderate

Sedimentation Rate, mm/yr

Shoals, flats	1.3-3.2

Bottom Sediment

Precent Mud Area	86
Percent Sand Area	13
Percent Organic Carbon, Av. %	2.2

Dominant Pattern:

Sand in entrance passages and erosion zones.

Mud on shoals and flats of inner reaches, basins and behind islands.

Pollution Susceptibility

Low due to high flushing ability and intermediate particle trapping efficiency.

Data Quality, Bottom Sediment Texture

Highly certain

*For total sediment

SEDIMENT CHARACTERIZATION

N120 MASSACHUSETTS BAY

Description

Massachusetts Bay is an elongate, arcuate embayment on the inner continental shelf between depths of about 20 and 75 m. It is bounded (according to NOAA NEI boundaries) by Cape Ann on the north and Brant Rock on the south but open to the Gulf of Maine on the east. Its bathymetry is very irregular as a result of the glaciation and sea-level fluctuations. The history is similar to that of Boston Bay. The last glacial retreat about 10,000 years ago was followed by submergence and a still-stand about 3,000 years ago. For the last 3,000 years sea-level has risen at about 1.5 mm/yr (Gornitz and Lebedeff, 1987) and surface sediments have been reworked by waves and currents similar to the present (Knebel, 1993). Short-term submergence rates are about 3.0 mm/yr (Emery and Aubrey, 1991).

Sediment Sources

The input from rivers is very low because the drainage basin is small and major streams have been dammed (Mencher *et al.*, 1968). Some fine material comes from Merrimack River discharge during river floods that extend plumes offshore and southward (Bothner and Butman, 1990). Small amounts of sediment may be supplied by shore erosion of headlands along the south coast. Others come in small amounts from Boston Bay (Knebel, 1993). In general, most of the Bay is starved of fine sediments because of low input. Most sediments are relic glacier deposits, derived from the last glaciation.

Pathways

Fine sediment is transported by currents driven seasonally by different mechanisms. In winter near-bottom currents over shoals are driven by wind stress of storms (Butman, 1978) and directed southwestward off Cape Ann and southeastward off Brant Rock. In deep water (> 65 m) currents are often directed opposite to the wind. In spring currents are driven by density variations set up by freshening of the Merrimack River north of the Bay. Near-bottom flow is weakly clockwise in deep water (> 65 m) and westward into Boston Bay. In fall southeasterly winds drive a northerly flow off Brant Rock and a northeasterly flow off Cape Ann (Butman *et al.*, 1992). Near-bottom tidal currents are weak (< 10 cm/s) but stronger (> 20 cm/s) toward Boston Harbor approaches (Knebel, 1993). Near-bottom mean flow is generally less than 8 cm/s (Butman *et al.*, 1992). Storm waves in late fall and early spring are large enough to cause episodic resuspension and reworking of bottom sediments throughout most of the Bay (Knebel, 1993).

Sinks

The main sink of mud accumulation is in deep water (> 55 m) near the seaward boundary of the Bay. This is the edge of a large basin, the Stellwagon Basin. These sediments reportedly accumulate under tranquil conditions, mainly during non-storm periods. Rates of accumulation are probably < 1.0 mm/yr, which was measured in the Stellwagon Basin (Hunt *et al.*, 1992). Elsewhere in the Bay (< 55 m depth) accumulation is restricted to local bathymetric lows (Knebel, 1993). Sediments eroded from headlands are likely distributed to beaches, spits and the adjacent shoreface.

Bottom Sediments

Mud (> 80%) is most abundant in deep offshore zones near the Bay's seaward boundary (Figure 1A). At shoaler depths (55 - 70 m) this grades to 40 to 80% mud whereas most of the Bay sediments are < 40% mud except locally in bathymetric lows of the west central sector where mud ranges 60 to 80% of the total sediment (Figure 1A). Some of these patches may represent historic dredged material removed from Boston Harbor (Willett *et al.*, 1972).

The distribution of coarse sediment types is best illustrated in a chartlet compiled by Willett *et al* (1972) reproduced by Meisburger (1976). Boulder and cobble sediments are most common off Boston Bay and farther southward whereas fine sand dominates to the north of the Bay. The coarse material is part of a thin veneer of reworked glacial drift whereas the fine sand is ascribed to progradation of sand from nearshore zones (Meisburger, 1976).

Contamination Status

At present Massachusetts Bay is likely among the least susceptible systems in the nation. This is by virtue of low population density on its shore flanks, good flushing and dominance of near-oceanic water. The Bay likely receives some far-field contaminants via fine sediment transport from Boston Bay and the Merrimack River (Cahill and Imbalzano, 1991). Fine sediments from the central Bay yield contaminants like fly ash, coal particles, elevated trace metals and bacterium spores (Knebel, 1993). After a large sewage outfall is completed in 1995, western sectors of the Bay will be subject to near-field nutrient and toxic impacts (Butman *et al.*, 1992).

Bottom Sediment Charts

The bottom sediments of Massachusetts Bay (Figure 3A) have been charted from 99 bottom samples collected by Cooks *et al* (1976), Willett *et al* (1972), Schlee *et al* (1973) as compiled and reported by Hathaway (1971), the U.S. Geological Survey (1989) and Cahill and Imbalzano (1991). Stations of Cooks and Willett were located on transects transverse to the shore about 2 km apart. Navigational control was provided by Loran type B hyperbolic radio location. A Shipek grab sampler and Alpine vibracorer were used to acquire samples. Bottom sample analyses supplement side-scan sonar and sub-bottom profile coverage as well as bottom photography.

The survey of Meisburger (1976) (Figure 3B) acquired core samples from selected stations located on a geophysical track grid with a 2 km spacing. A vibracorer was used to acquire bottom samples and supplemented with bottom grabs. Sediment analyses are based on the Wentworth classification.

The distribution of mud abundance (Figure 3A) is classified into three groups and mapped by computer. This classification displays major patterns for recognizing dominant features. The chartlet was compiled using a minimum mappable unit of 1 km^2. Numerous isolated patches are not represented. The chartlet of textural variations (Figure 3B) is taken from Meisburger (1976) as based on data of Willett *et al.* (1972) and others. It is based on both general lithology and single sample analyses from about 125 stations including many from Willett *et al.* (1972) used in the mud percentage distribution (Figure 3A).

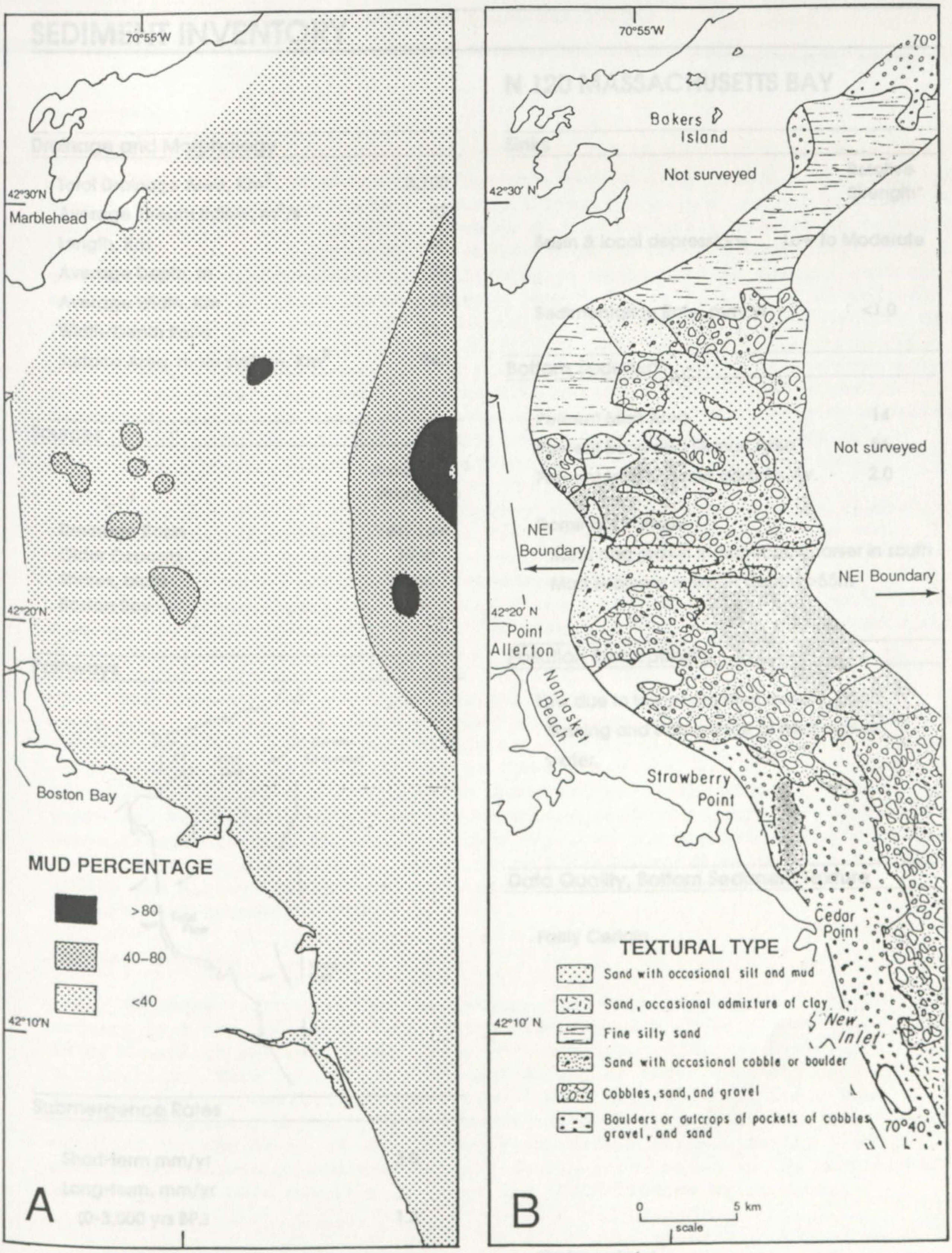


Figure 3A. Distribution of mud abundance mapped by computer from data files of U.S. Geological Survey (1989) and Hathaway (1971).

Figure 3B. Distribution of textural types reproduced from Meisburger (1976).

SEDIMENT INVENTORY

N 120 MASSACHUSETTS BAY

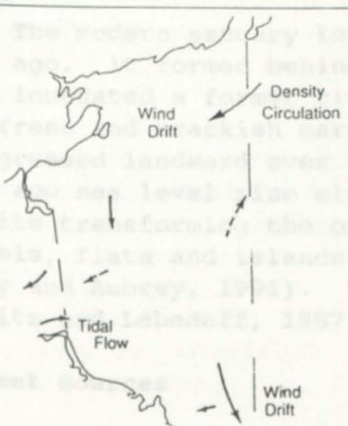
Drainage and Morphology

Total Drainage Area, Km^2	3,100
Average Stream Inflow, m^3/s	82
Length, Km	58
Average Depth, m	24
Average Width, Km	20
Width/Depth Ratio	833
Surface Area, main system, Km^2	943

Sources

	Relative Strength*
Drainage Basin	Very Low
Older Deposits	High
Shores, bluffs	Low
Boston Bay	Low

Pathways



Submergence Rates

Short-term mm/yr	3.0
Long-term, mm/yr (0-3,000 yrs BP.)	1.5

Sinks

	Relative Strength*
Basin & local depressions	Low to Moderate

Sedimentation Rate, mm/yr	<1.0

Bottom Sediment

Percent Mud Area	14
Percent Sand and Gravel Area	86
Percent total organic carbon, Av.	2.0

Dominant Pattern:

Sand and gravel throughout, coarser in south

Mud seaward in water depths >55m

Pollution Susceptibility

Low due to low population density, good flushing and dominance of near-ocean water.

Data Quality, Bottom Sediment Texture

Fairly Certain

*For fine sediment

N110 MERRIMACK RIVER

Description

The Merrimack River is a river estuary with relatively moderate river discharge and low fluvial sediment influx except during floods. The drainage area is partly rural and partly industrialized; therefore the estuary receives contaminants from both industrial wastes as textile mills as well as domestic sewage and numerous agricultural-induced non-point sources including pesticides and insecticides. Shellfishing is restricted in seaward sections of the system. Entrance reaches have a long (150 yr) history of shoreline change and jettying (Hayes, 1969; Curren and Chatham, 1979). The jetties trap littoral drift moving south along Salisbury Beach, as well as sandy material moved through the entrance by flood currents. Additionally, dikes were built across "The Basin", besides weir-like breakwaters west of Plum Island and Woodbridge Island, in hopes of increasing current speed and reducing shoaling in the main entrance (Hartwell, 1970). Dredging is mainly limited to a channel, 3.6 m deep, through the jetties and contiguous offshore shoals.

The estuary has a narrow meandering subtidal channel that is flanked in the seaward half by extensive intertidal flats rich in worms, clams and mussels. Secondary channels and numerous tidal creeks branch off from the main channel running around marsh islands and draining more than 16.9 km^2 of salt marsh. The estuary has a complex flood tidal delta near the mouth and a deep narrow channel near the head. The mean tide range is 2.5 m at the mouth and 1.5 m at Haverhill.

The modern estuary is a relatively young feature forming less than 6,000 years ago. It formed behind a barrier island when the most recent rise of sea level inundated a former river valley filled with glacial deposits and fringed with fresh and brackish marsh. As sea level rose sand and mudflat sediments transgressed landward over the marsh deposits (Hartwell, 1970). About 3,000 years ago sea level rise slowed and marshes spread over flats and open bay deposits transforming the original open Bay into the present system with tidal channels, flats and islands. Submergence proceeds today at about 1.8 mm/yr (Emery and Aubrey, 1991). This contrasts to a long-term rate of 1.5 mm/yr (Gornitz and Lebedeff, 1987).

Sediment Sources

Sediment is supplied to the estuary from multiple sources. Since the estuary is river dominated during high discharge and river floods (Hartwell, 1970) bear high sediment loads, fine sediment input from the river is likely substantial. This is despite the scant amount of loose soil and dams in the drainage basin. Small amounts are also likely supplied from local bank erosion of glacial deposits in the upper estuary, as well as from erosion of headlands on the ocean shore. In contrast, much material, mainly sand and some fines, probably come from glacial debris left behind on the continental shelf that has been reworked by waves and redistributed by currents.

Pathways

Fine sediment within the estuary is transported by tidal currents and the superimposed estuarine circulation. Ebb currents are largely confined to channels and near-surface water where they reach 1.5 m/s or two times flood currents. Flood currents dominate in near-bottom water and along the north side. They are responsible for landward sand transport in the lower estuary and for channel scour (Hartwell, 1970). Fines winnowed from the channel floor are carried over and deposited on adjacent intertidal flats. Flood currents, which dominate at low river discharge, also build a sandy flood tidal delta near the mouth (Hartwell, 1970). Cross bedding and megaripples are the predominant delta structures.

The river-borne suspended material partly follows the estuarine circulation, which is a partially mixed (Type B) regime during normal or high river discharge: (1) seaward through freshwater reaches, (2) seaward through the upper estuarine layer, being stronger on the south side, and downward by settling especially on Joppa Flats, (3) landward through the lower layer to the inner salt limit 8 to 12 km landward of the mouth, vicinity of Carr Island and Salisbury Point (Hartwell, 1970). Prior to accumulation fine sediment undergoes repeated tidal cycles of settling, deposition and resuspension. Since plumes of fine sediment extend off the mouth and southward in the coastal drift, some fine material must escape the estuary.

Sinks

The main sink of mud accumulation is on Joppa Flats and the channel south of Woodbridge Island (Hartwell, 1970). Alternately, much material accumulates in the head of secondary tidal tributaries and adjacent marshes. The flood tidal delta is a focus of sand accumulation.

Bottom Sediments

Sediments are dominantly sand. Gravelly sand, which is moderately to well-sorted, is abundant in the main channel and on the flood tidal delta (Hartwell, 1970). Muddy sand as well as mud, which is poorly sorted, is abundant on intertidal flats, especially Joppa Flats. Mixtures of sand and mud, which are poorly sorted, occur in secondary tidal channels (Hartwell, 1970). Bedrock occurs locally on the channel floor and shell banks of mussels are abundant on intertidal flats, especially at the Plum Island River mouth (Jerome *et al.*, 1965).

Contamination Status

The Merrimack River estuary is among the most susceptible systems among the nation's estuaries (Biggs *et al.*, 1989). Although flushing ability is high and particle retention efficiency low, the human population in the drainage basin relative to estuary surface area is high. Additionally, there is a high degree of agriculture activity plus chemical and metal activity, in the drainage basin relative to estuary surface area (Biggs *et al.*, 1989).

Bottom Sediment Charts

The bottom sediments of the Merrimack River estuary (Figure 4) have been charted from 73 grab samples collected and analyzed for grain size by Hartwell (1970). Positioning and collection techniques are not reported. A computer file was compiled from station positions displayed on a chartlet of cross profiles and values of mean size. The profile sampling transects are located at about 0.8 to 1.0 km intervals.

The distribution of mean grain size is classified by whole phi intervals into seven groups and mapped by computer. The chartlet (Figure 4) was compiled using a minimum mappable unit of 0.03 km^2. Narrow transition zones of size are not represented.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

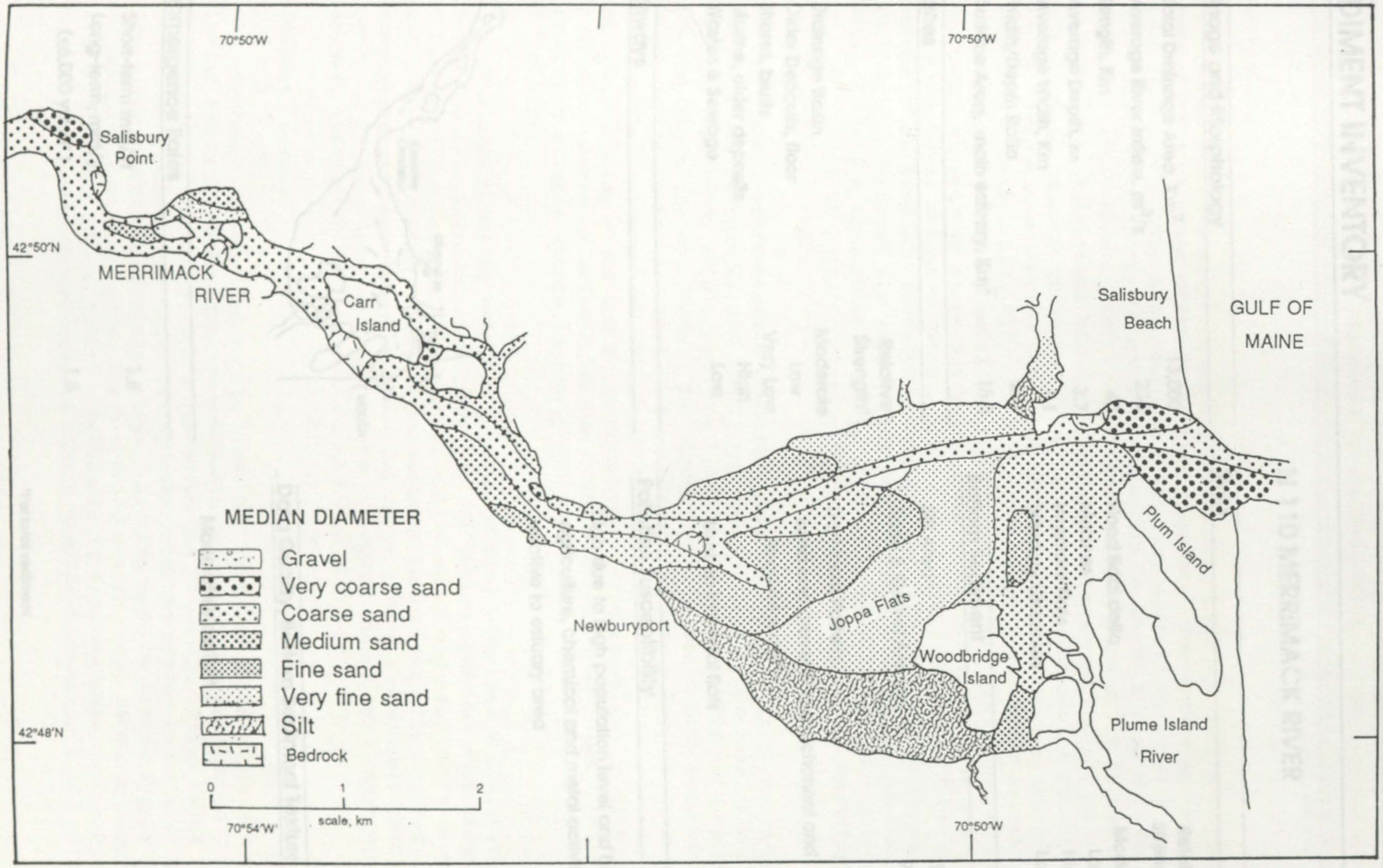


Figure 4. Distribution of mean grain size mapped by computer. From charts and data of Hartwell (1970). Size classes follow the Wentworth classification.

SEDIMENT INVENTORY

N 110 MERRIMACK RIVER

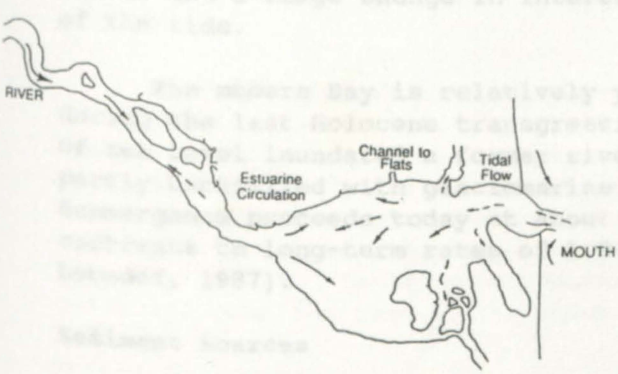
Drainage and Morphology

Total Drainage Area, Km^2	13,000
Average River Inflow, m^3/s	236
Length, Km	40
Average Depth, m	3.7
Average Width, Km	1.1
Width/Depth Ratio	297
Surface Area, main estuary, Km^2	15.5

Sources

	Relative Strength*
Drainage Basin	Moderate
Older Deposits, floor	Low
Shores, bluffs	Very Low
Marine, older deposits	High
Wastes & Sewage	Low

Pathways



Submergence Rates

Short-term mm/yr	1.8
Long-term, mm/yr (≤6,000 yrs BP.)	1.5

Sinks

	Relative Strength*
Flood tidal delta	Moderate
Marshes	Low
Intertidal Flats	High
Tributary Channels	Low

Bottom Sediment

Silt Area	9
Sand & Gravel Area, %	91

Dominant Pattern:

Sand and gravel in main channel and flood tidal delta

Mud on intertidal flats

Pollution Susceptibility

High due to high population level and high agriculture, chemical and metal activity relative to estuary area

Data Quality, Bottom Sediment Texture

Moderately certain

*For total sediment

SEDIMENT CHARACTERIZATION

N100 GREAT BAY

Description

Great Bay is a river estuarine system that consists of the Piscataqua River, Little Bay, and Great Bay proper (Fig. 5). The system is fed by seven major freshwater tributaries but the total discharge is relatively small, 57 m^3/s. Thus, tidal currents are more important to overall flow than density-driven currents (Short, 1992). Mean tidal range varies 2.7 m at the mouth to 2.1 m near the Squamscott River entrance. The system is subject to anthropogenic impacts of sewage discharge and non-point source runoff. These produce microbial pollution with resultant shellfish closures, and nutrient loading with excess turbidity and loss of eelgrass. Additionally, there are historic inputs of heavy metal and toxic organics from tanneries and mills on the rivers as well as in recent years, from Pease Air Force Base and the Portsmouth Naval Shipyard (Short, 1992). A shipping channel 9.5 to 10 m deep extends 11 km landward up the Piscataque River from the Gulf of Maine. Dredging and disposal are largely limited to local pier slips, berths, cargo docks, petroleum facilities, and the Portsmouth Naval Shipyard. Disposed material, which is partly contaminated, provides landfill at the Shipyard (Short, 1992).

The shore configuration and bathymetry are structurally controlled. The axis of Great Bay proper and Little Bay coincides with the axis of the Great Bay syncline (Ward, 1992). And the Piscataqua River may lie in a northwest trending fault (Birch, 1984). The shoreline is bordered with extensive muddy intertidal flats and indented with numerous re-entrants and tributaries indicative of submergence. Estuarine tributaries are fringed with salt marsh the largest being along the Squamscott River. The shoreline is often bedrock fronted by cobble or shingle beaches. The flats give the Bays a shallow nature and a large change in intertidal area (Ward, 1992) with rise and fall of the tide.

The modern Bay is relatively young forming less than 7,500 years ago during the last Holocene transgression. It formed when the most recent rise of sea level inundated a former river valley which was previously glaciated, partly backfilled with glaciomarine sediment and subaerially exposed. Submergence proceeds today at about 2.2 mm/yr (Emery and Aubrey, 1991). This contrasts to long-term rates of 1.0 to 1.5 mm/yr (Haug, 1976; Gornitz and Lebedef, 1987).

Sediment Sources

Sediment is supplied to the Great Bay system from multiple sources. The fluvial input of coarse-grained sediments is likely low because most rivers were dammed in the early 1800's (Anderson and Tischler, 1971). Fine sediments, however, are still transported into the system especially during high river discharge of spring thaws. Eroding bedrock shores supply cobble and shingle that form narrow beaches while eroding till deposits supply sand to local beaches (Ward, 1992). The supply of fine sediment from shore deposits and adjacent drainage is likely limited because soil and till are thin and rocks resistant (Ward, 1992). Some sand and fines probably come from glacial debris on the inner shelf that is reworked by storm waves and redistributed landward by currents. Old glacier clay deposits exposed by local scour in channels walls are also a potential but small source of fine sediment (Haug, 1976).

Organic detritus is supplied by production in estuarine tributary marshes while shell is produced both in the tributaries and inner Great Bay by clams and oysters (NH Fish and Game, 1989).

Pathways

Sediment in the system is transported by tidal currents, at times in concert with wind waves. Ebb currents have greater speeds near the surface, with an average maximum of 2.3 m/s in constricted channels of the Piscataqua River, than flood currents which average about 1.5 m/s. Tidal currents are generally faster in lower reaches of the Piscataqua River than in Little Bay, (0.75 m/s) or in Great Bay (0.5 m/s) (Reichard and Celikkol, 1978). They are strongest in the central "core" than along sides or over flats (Swenson *et al.*, 1977).

Transport pathways of fine sediment are broadly organized into three subsystems; 1) a weak fluvial subsystem driven by river flow during high discharge through upper parts of estuarine tributaries, 2) a flat to channel subsystem whereby fines are eroded and resuspended by wave action (Anderson, 1972) or by ice in winter or spring and dispersed channelward, or bayward, down the suspension gradient (Ward, 1992). Alternately, fines are scoured or resuspended by tidal currents from the channel floor, and carried onto the flats and deposited by settling and biological trapping as filtering, biodeposition, and algal "packaging" (Anderson, 1983), 3) an entrance subsystem with landward transport of sand into seaward parts of the entrance channel (Mills, 1977).

Sinks

The main sink for long-term mud accumulation is on tidal flats of Great Bay. Rates of accumulation range 2.0 to 2.5 mm/yr (Leavitt, 1980). Deposition is enhanced by trapping of deposit feeders, algal binders and eelgrass especially during summer (Anderson, 1983). Additionally, marshes are a sediment sink in estuarine tributaries. A degree of fluvial accumulation occurs in the upper Piscataqua at rates of 1.6 to 7.8 mm/yr (Capuzzo and Anderson, 1973). These values contrast to a long-term rate based on sediment thickness over the past 8,000 years of 1.0 mm/yr (Haug, 1976).

Bottom Sediments

Sediment texture is distributed through a range of sand and silt percentages; clay is relatively scarce. Mud percentage, >80%, dominates tidal flats of Great Bay and estuarine tributaries of the Oyster River, Bellamy River, and Lamprey River (Fig. 5A). In contrast, sand and silty sand floors the Piscataqua River channel, central Little Bay, and central Great Bay. The entrance channel of the Piscataqua River is dominantly sand and gravel (Mills, 1977). These broad distributions tend to follow an energy format controlled by tidal currents.

Organic carbon content ranges from 0.2% in sand of the tidal channel to 13.2% in clayey silt from the Lamprey River (Armstrong, 1974). Estuarine tributaries, except for the upper Piscataqua River, have relatively high values especially in fine sediment.

Contamination Status

In terms of pollution susceptibility Great Bay has a relatively low efficiency to retain fine particles (U.S. NOAA, 1990). Its moderate population density however, in addition to substantial metal and chemical activity besides moderate agricultural activity relative to estuary area, likely favor a moderate to high pollution susceptibility among U.S. Systems.

Bottom Sediment Charts

Bottom sediments of the Great Bay system (except for the lower Piscataqua River) were sampled by Armstrong (1974; 1975) from 80 cores and grab samples. The stations are spread across the bays and channel axes at about 0.3 to 1.0 km intervals. Locations were positioned mainly by sextant on known buoys or landmarks. In channels a ship's radar aided positioning. Grain size was analyzed by wet sieving and pipetting. In the upper Piscataqua River seven additional samples were utilized from cores of Capuzzo and Anderson (1973).

The distribution of mud abundance (Fig. 5A) is broadly classified into three classes. This classification displays dominant patterns but not all spatial detail. The chart was compiled using a minimum mappable unit of 0.1 km^2 and smoothing isolines. Small isolated patches are not shown. Greater detail can be obtained by mapping the original data at larger scales and smaller class intervals.

Figure 5B shows the distribution of sediment texture based on the Shepard classification (triangle). The chart was compiled using a minimum mappable unit of 0.1 km^2. Consequently, narrow transition zones are not represented. For great detail the original data should be mapped at a larger scale.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

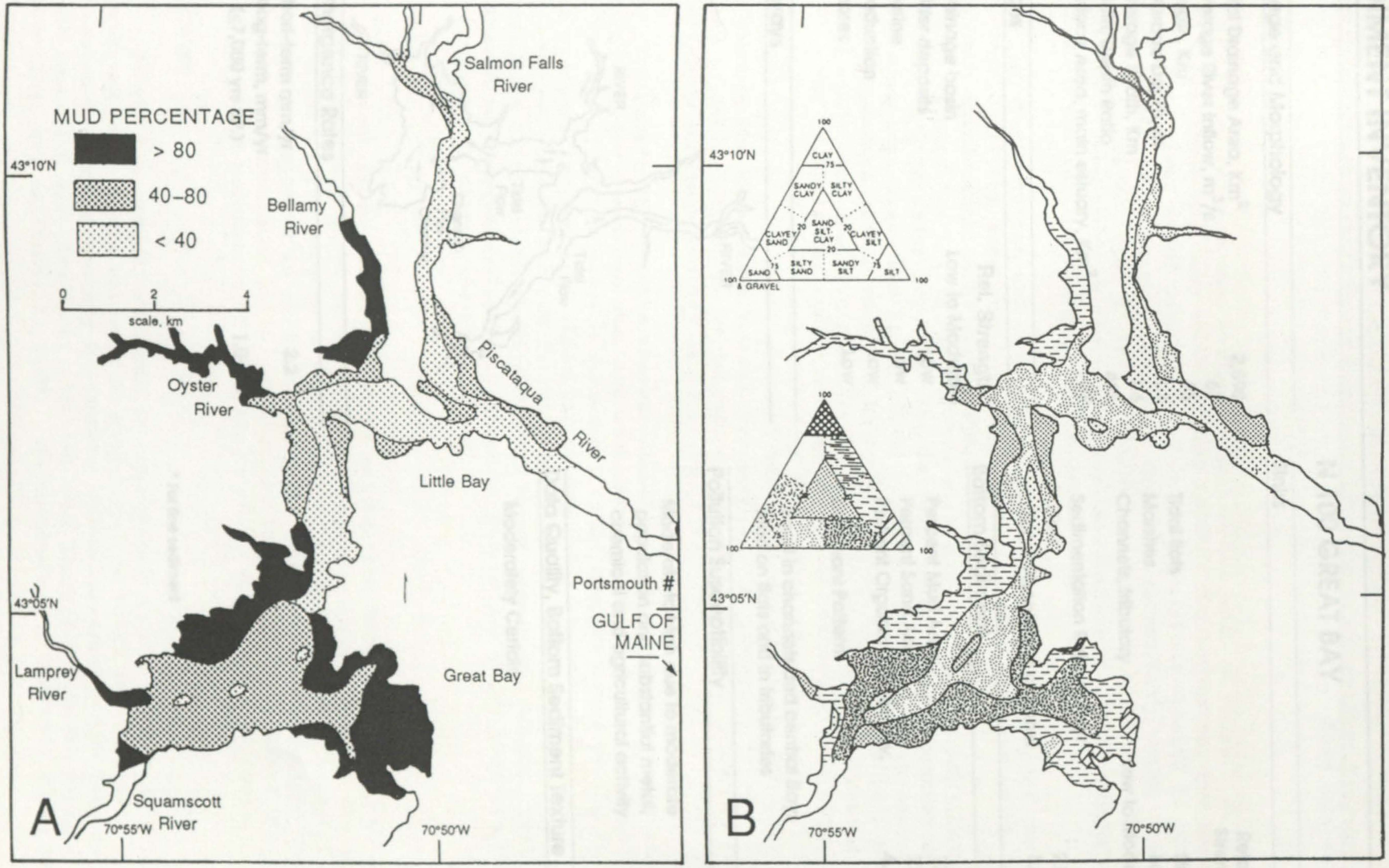


Figure 5A. Distribution of mud abundance mapped from Armstrong (1974), Armstrong *et al.* (1976) and Cupuzzo and Anderson (1973).

Figure 5B. Distribution of textural types following Shepard classification from same sources as Fig. 5A.

SEDIMENT INVENTORY

N 100 GREAT BAY

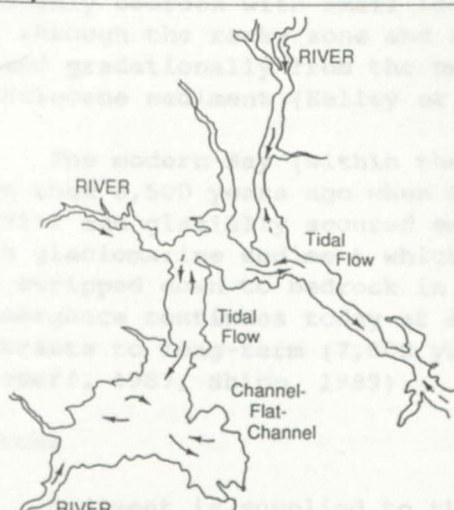
Drainage and Morphology

Total Drainage Area, Km^2	2,590
Average River Inflow, m^3/s	57
Length, Km	25
Average Depth, m	3.3
Average Width, Km	1.6
Width/Depth Ratio	485
Surface Area, main estuary, Km^2	39

Sources

	Rel. Strength*
Drainage basin	Low to Moderate
Older deposits	Low
Marine	Low
Production	Low
Shores	Low

Pathways



Submergence Rates

Short-term mm/yr	2.2
Long-term, mm/yr (≤7,000 yrs BP.)	1.0-1.5

Sinks

	Relative Strength*
Tidal flats	High
Marshes	Low
Channels, tributary	Low to Moderate

Sedimentation Rate, mm/yr

Flats	2.0-2.5
Upper Piscataqua channel	1.6-7.8

Bottom Sediment

Percent Mud Area	73
Percent Sand Area	27
Percent Organic Carbon, Av.	4.1

Dominant Pattern:

Sand in channels and central Bays
Mud on flats and in tributaries

Pollution Susceptibility

Moderate to high due to moderate population and substantial metal, chemical and agricultural activity

Data Quality, Bottom Sediment Texture

Moderately Certain

* For fine sediment

SEDIMENT CHARACTERIZATION

N090 SACO BAY

Description

Saco Bay is an arcute embayment open to the Gulf of Maine. It is shaped by rock headlands and long sandy barrier spits. Two estuaries, the Saco River and Scarboro River enter near the headlands. Population density in the drainage basin is relatively low, less than 185 persons/km^2, urban, industrial and agricultural activity is low. Contaminant input, i.e. metals and domestic sewage comes from towns on the Saco River, Biddleford and Saco. Dredging is limited to the jettied entrance of the Saco River.

The configuration and bathymetry are divided into four zones (Kelley *et al.*, 1986). 1) The inner zone consists of estuaries and mouths of the rivers. These are mainly intertidal subsystems (mean tidal range is 2.5 m). Whereas the Saco estuary has valley walls, thin sand deposits and a steep gradient with limited intertidal features, the Scarboro estuary has extensive marshes, a few intertidal flats and thick (60 m) sediment deposits. 2) A nearshore ramp zone seaward of the beach to 15 to 20 m water depth. This is a gently sloping sandy zone that steepens farther seaward to 30 m and in places, is interrupted by shelf valleys or a rocky zone. 3) The rocky zone has an irregular surface due to large boulders and ledges up to 5 m high. The zone is mainly bedrock with small isolated basins of sediment. 4) Shelf valleys cut through the rocky zone and are bordered by steep bedrock walls. They extend gradationally from the nearshore ramp and contain a thickness (8-12 m) of Holocene sediment (Kelley *et al.*, 1987).

The modern Bay (within the NEI boundary) is relatively young forming less than 6,500 years ago when the most recent rise of sea level inundated a fluvial and glacially scoured embayment. This embayment was partly filled with glaciomarine sediment which was subsequently reworked and eroded by waves and stripped down to bedrock in outer parts of the bay (Kelley *et al.*, 1986). Submergence continues today at about 2.2 mm/yr (Emery and Aubrey, 1991). This contrasts to long-term (7,000 yr) rates of 0.9 to 1.5 mm/yr (Gornitz and Lebedeff, 1987; Shipp, 1989).

Sources

Sediment is supplied to the bay mainly from local sources, i.e. old glacial deposits scoured from the floor. Fluvial input from the drainage basin is likely low because of dams and lack of erodable soil except for old glaciomarine deposits in river banks. Fine sediment likely escapes the bay rather than accumulates in it. Production in marshes contributes organic material while production of epifauna in rocky zones supplies shell.

Pathways

In the bay proper, sediment is transported mainly by wave action and associated wave-driven currents whereas tidal currents are important in the estuaries and around estuary entrances. Flood currents in the Saco estuary, which reach 1.0 m/s, transport littoral sand through the mouth resulting in flood tidal deltas (Farrell, 1970). In contrast, ebb currents which reach

1.2 m/s transport fluvial sand seaward. Historically they resulted in an ebb tidal delta which is largely destroyed by jettying. Since the Saco estuary, which is partly mixed, it has an estuarine circulation (Farrell, 1970) that favors landward transport and entrapment of fine sediment within the estuary.

In the bay nearshore zone, southeast wind combines with refracted swell to generate a longshore drift that moves fine sand north toward Pine Point. Whereas northeast storm waves move sand southward in the south sector they also move it north in the north sector, i.e. toward Pine Point. In the bay proper waves resuspend sandy sediment from the nearshore ramp and wave driven currents likely transport it seaward. Material reaching shelf valleys probably continues farther seaward but the nature of the movement is unknown.

Sinks

The main sink for fluvial mud is the marshes of the Scarboro estuary and behind the spit at Pine Point. Sand accumulates in tidal deltas, beaches and barrier spits. In the bay proper some sand accumulates in the nearshore ramp whereas another part accumulates, together with mud, in the shelf valleys. Rocky zones are mainly erosional but some sand or gravel accumulates locally between bedrock outcrops. Most mud is found farther seaward in the outer basins (Kelley *et al.*, 1987).

Bottom Sediments

Sand is a dominant bottom type in the nearshore ramp zone less than 15 to 20 m. Mud percentages in this zone are low, mainly less than 20%, Figure 6. Although sand occurs farther seaward, the percentage of mud generally increases and thus, sorting diminishes. Bedrock surrounds small islands of the central bay and north of Biddleford Pool. Gravel occurs in patches either in the rock zones or adjacent to them at depths less than 50 m, where it is often mixed with sand.

Contamination Status

Although the drainage basin area to estuary area is relatively high, pollution susceptibility of Saco Bay ranks low because of limited industrial, chemical and agricultural activity (Biggs *et al.*, 1989). Additionally, the bay proper is well mixed and likely has good flushing.

Bottom Sediment Charts

The bottom sediments of Saco Bay were sampled and charted by Kelley *et al.* (1987). Within the NEI boundary across the inner bay, 89 samples were collected with a Smith-MacIntyre grab. Stations were occupied on a grid at 0.5 to 1.0 km intervals. Positioning was accomplished by Loran C intersections. As noted by the workers the gravel portion is probably under-represented because of the difficulty of sampling coarse material with a grab. Laboratory analyses followed procedures of Folk (1974). Gravel was sieved, sand analyzed in a settling tube and mud analyzed with a Sedigraph. The grab samples, besides submersible observations, provided "ground truth" and verification for interpretation of textural patterns from side scan sonar records and from 3.5 kHz seismic reflection profiles.

The distribution of mud abundance (Fig. 6) is classified into three groups and mapped by computer. The bedrock distribution is taken from Kelley *et al.* (1987). This classification displays major patterns for recognizing dominant features. The chartlet was compiled using a minimum mappable unit of 0.2 km^2. Narrow transition zones of texture are not represented. Greater detail can be acquired by mapping the original data at larger scales and smaller mud class intervals.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

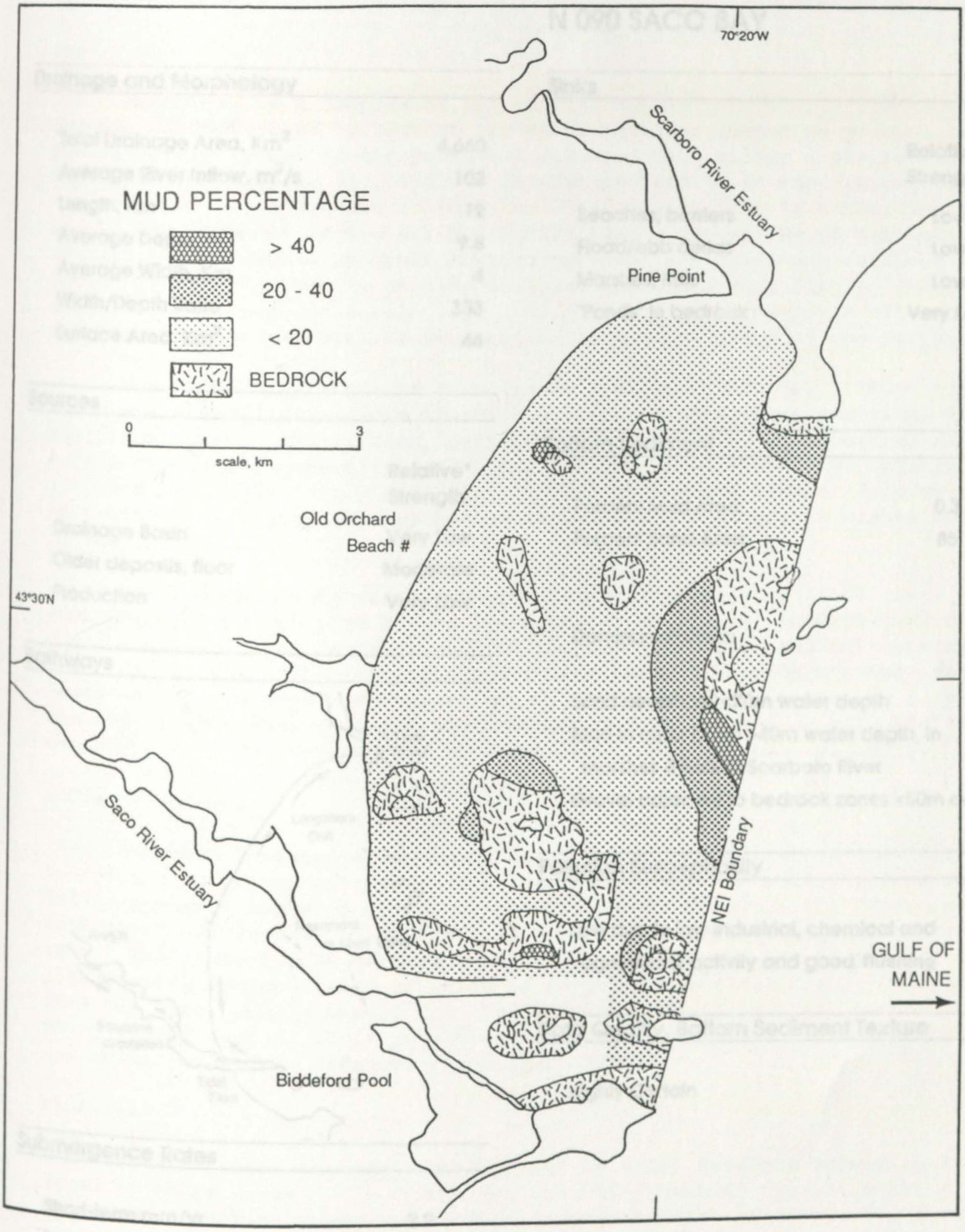


Figure 6. Distribution of mud percentage in Saco Bay based on data of Kelley *et al.* (1987).

SEDIMENT INVENTORY

N 090 SACO BAY

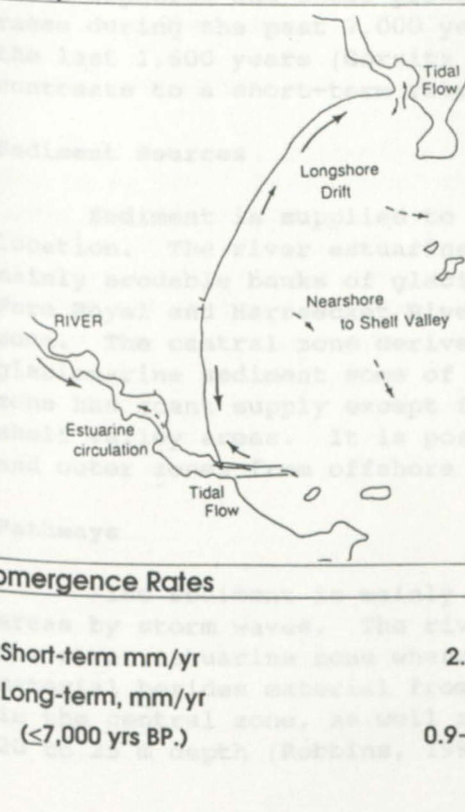
Drainage and Morphology

Total Drainage Area, Km^2	4,660
Average River Inflow, m^3/s	102
Length, Km	12
Average Depth, m	9.8
Average Width, Km	4
Width/Depth Ratio	333
Surface Area, Km^2	44

Sources

	Relative* Strength
Drainage Basin	Very Low
Older deposits, floor	Moderate
Production	Very Low

Pathways



Submergence Rates

Short-term mm/yr	2.2
Long-term, mm/yr (≤7,000 yrs BP.)	0.9-1.5

Sinks

	Relative* Strength
Beaches, barriers	Low
Flood/ebb deltas	Low
Marshes, flats	Low
"Ponds" in bedrock	Very Low

Bottom Sediment

Percent Mud Area	0.3
Percent Sand Area	85

Dominant Pattern:

Sand nearshore <20m water depth

Mud in outer basin >40m water depth, in marshes & flats of Scarboro River

Gravel adjacent to bedrock zones <50m depth

Pollution Susceptibility

Low due to low industrial, chemical and agricultural activity and good flushing

Data Quality, Bottom Sediment Texture

Highly Certain

*For fine sediment

SEDIMENT DESCRIPTION

Description

Casco Bay is a complex of narrow bays and islands with a distinctive morphology controlled by bedrock structure. It was shaped by glacial ice moving nearly normal to the bedrock strike and thus termed a strike-normal embayment (Belknap *et al.*, 1987). Population density in the drainage basin is substantial; it is focused in Portland, the largest port in Maine, in the south, and Freeport in the north. Agriculture occupies 10% of the basin and fertilizer, augmented by urban sewage, provides a significant nutrient input (NOAA, 1990). The bay is heavily utilized for commercial fishing (Larsen *et al.*, 1983). Dredged channels lead into Portland to accommodate oil tankers and most dredged material is disposed in open water sites of the southern Bay.

The bathymetry exhibits three zones (Kelley, 1986; Hay, 1988): 1) a river estuarine (inner) zone (including coves) with marshes and tidal flats, including mussel (shell) bars, backed by stable bluffs, 2) a central bay zone with a flat floor generally less than 20 m deep with a chain of islands and landward, extensive intertidal flats backed by eroding bluffs, 3) a deep outer zone with an irregular bottom and submerged bedrock ridges in depths between 20 and 70 m.

The modern Bay is relatively young forming less than 7,500 years ago when the most recent rise of sea level inundated glacial scoured rock ridges and glacially filled depressions. During the rise waves and currents reworked older deposits and these processes continue today. Long-term submergence rates during the past 7,000 years are 0.5 to 1.5 mm/yr with slower rates in the last 1,500 years (Gornitz and Lebedeff, 1987; Belknap *et al.*, 1989). This contrasts to a short-term rate of 2.2 mm/yr (Emery and Aubrey, 1991).

Sediment Sources

Sediment is supplied to Casco Bay from different sources that vary with location. The river estuarine zone receives a range of material from rivers, mainly erodable banks of glaciomarine fine sediment, e.g., the Presumpscot, Fore Royal and Harrsecket Rivers, and by tidal recycling from the central bay zone. The central zone derives material from bluff erosion of glacial till or glaciomarine sediment some of which is recycled via tidal flats. The outer zone has scant supply except for slow erosion of headlands and high energy shelf valley areas. It is possible some fine material is introduced to inner and outer zones from offshore (Schnitker, 1974).

Pathways

Fine sediment is mainly transported by tidal currents augmented in shoal areas by storm waves. The rivers are the chief path of fluvial material to the river estuarine zone whereas tidal currents likely redistribute fluvial material besides material from the central zone. Wave eroded bluff material in the central zone, as well as material resuspended by storm waves above the 20 to 25 m depth (Robbins, 1992) is also redistributed by tidal currents, both landward and seaward, along flats and through channels (Belknap *et al.*, 1986). Additionally, slumping assists transport of margin material, including organic detritus, into deeper water. Tidal currents, augmented by slumping, are likely significant in transporting material seaward from the central zone to the deep outer zoned (Robbins, 1992).

Sinks

The diverse pathways lead to a variety of sinks. The main sink of mud accumulation is shallow depressions and floors of the central zone which are protected by islands and peninsulas. Additionally, mud accumulates on intertidal flats and fills narrow depressions and channels of shelf valleys as well as basins of the outer zone. Landward, mud accumulates in intertidal flats with rates in the range of 0.3 to 17.5 mm/yr (Smith, 1990; Hay, 1988).

Bottom Sediments

Mud is the most extensive sediment type. Percentages > 80% cover the flat-bottomed central region (Fig. 7). It occurs landward on intertidal flats (Smith, 1990), in coves and river mouths. Mussel bars (shell) are reported in mud-rich zones (Smith, 1990; Robbins, 1992). Mud (> 40%) also covers channels and shelf valleys of the outer zone (Kelley *et al.*, 1987). In contrast, low mud percentages, i.e., sand and gravel, occur in bedrock depressions and channels of the outer zone. A patch of silty sand occurs just west of Cape Small. Bedrock, which is stripped of sediments, is a prominent bottom type around islands and submerged ledges.

Organic carbon ranges 0.1 to 61.0% with an average of 3.6%. Relatively high values come from high mud zones whereas low values come from sand and gravel samples (Robbins, 1992).

Contamination Status

In terms of pollution susceptibility among the nations estuaries, Casco Bay ranks low. It is among the least susceptible with respect to population level, metal and agricultural activity relative to bay area (Biggs *et al.*, 1989). Additionally, the bay is well-mixed by tidal currents and therefore likely well flushed. Sediments are contaminated with trace metals in Portland Harbor and in the lower Fore River but reduced to low concentrations in most of the bay (Larsen *et al.*, 1983).

Bottom Sediment Charts

Bottom sediments of Casco Bay were sampled by Robbins (1992) and by Larsen *et al.* (1983). In Robbin's survey 71 stations were occupied within National Estuarine Inventory boundaries at grid intervals of about 1.8 km. Loran-C provided navigational control. Grain size and percentage sand-silt-clay by sieving and pipette. In Larsen's survey 32 grab samples were obtained for organic carbon and textural analyses. Positioning and station design is not reported, however a greater density of stations, approximately 1.0 km intervals, are located near Portland than in the northern Bay which are at about 4.0 km intervals.

The distribution of mud abundance (Fig. 7) is classified into three groups and mapped by computer. The bedrock distribution is taken from Kelly *et al.* (1987). This classification displays major patterns for recognizing dominant features. The chartlet was compiled using a minimum mappable unit of 0.5 km^2. Narrow transition zones of texture are not represented. Greater detail can be acquired by mapping the original data at larger scales and smaller mud class intervals. The abundance of gravel is likely under-represented by sampling because of the difficulty of collecting large material in a grab or core.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

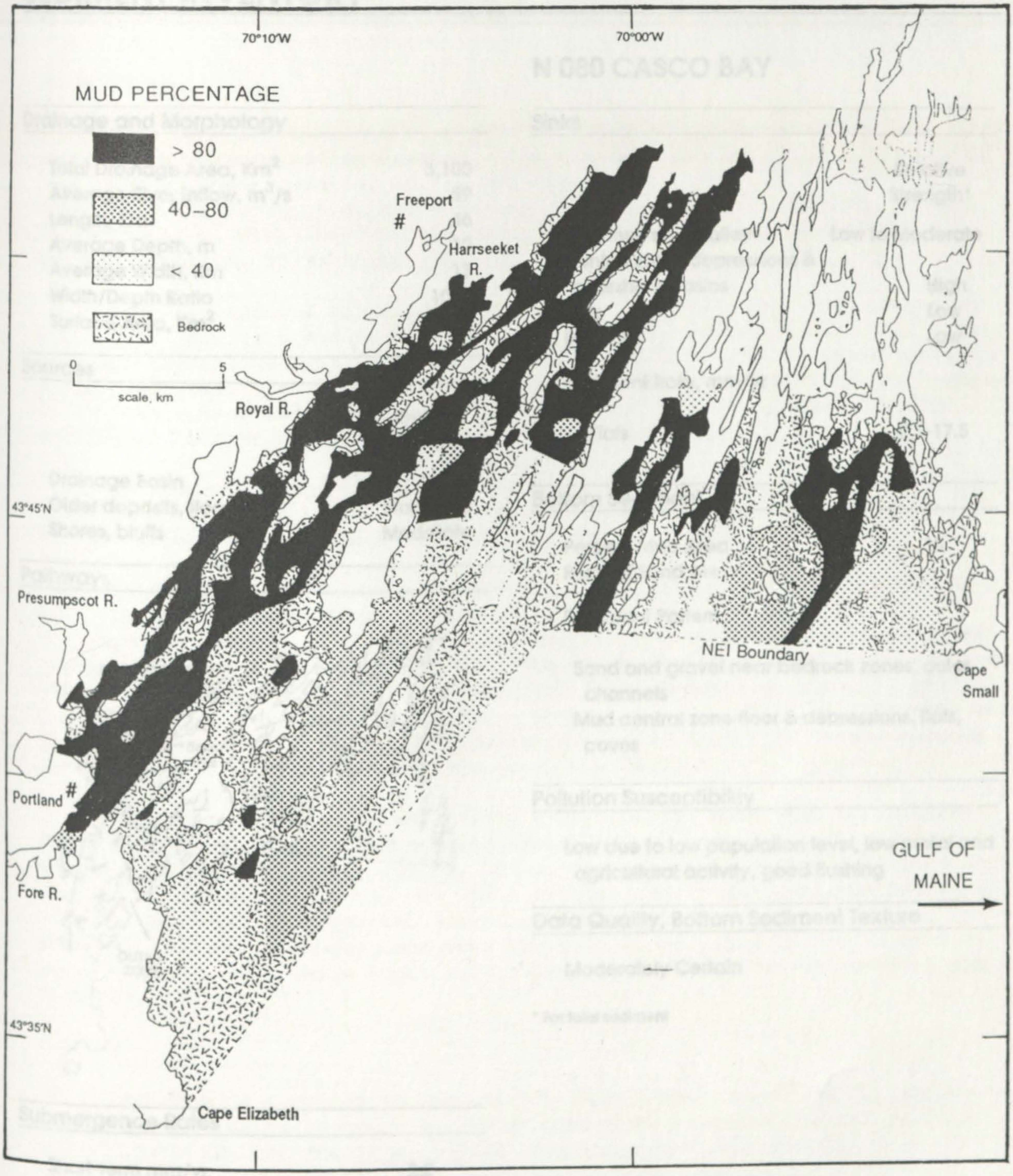


Figure 7. Distribution of percentage mud in Casco Bay based on data from Robbins (1992) and Larsen (1983) with bedrock from Kelley *et al.* (1987).

SEDIMENT INVENTORY

N 080 CASCO BAY

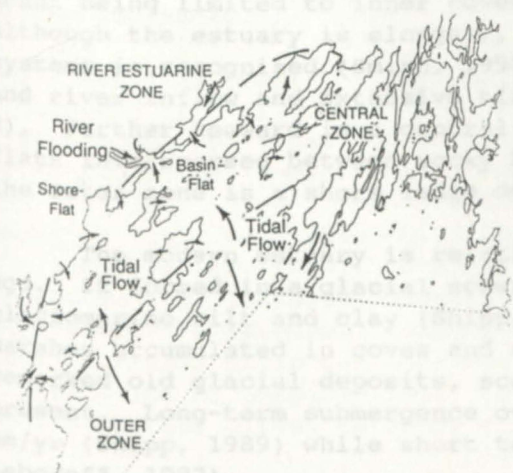
Drainage and Morphology

Total Drainage Area, Km^2	3,100
Average River Inflow, m^3/s	59
Length, Km	46
Average Depth, m	12
Average Width, Km	13
Width/Depth Ratio	1080
Surface Area, Km^2	425

Sources

	Relative Strength*
Drainage Basin	Low
Older deposits, floor	Moderate
Shores, bluffs	Moderate

Pathways



Submergence Rates

Short-term mm/yr	2.2
Long-term, mm/yr (≤7,000 yrs BP.)	0.5-1.5

Sinks

	Relative Strength*
Channel, shelf valley	Low to Moderate
Central zone, depressions & nearshore basins	High
Flats	Low
Beaches	Low

Sediment Rate, mm/yr

Flats	0.3-17.5

Bottom Sediment

Percent Mud Area	18
Percent Sand Are	-

Dominant Pattern:

Sand and gravel near bedrock zones, outer channels
Mud central zone floor & depressions, flats, coves

Pollution Susceptibility

Low due to low population level, low metal and agricultural activity, good flushing

Data Quality, Bottom Sediment Texture

Moderately-Certain

* For total sediment

SEDIMENT CHARACTERIZATION

N070 SHEEPSCOT BAY, DAMARISCOTTA RIVER

Description

Sheepscot Bay consists of a glacially sculpted embayment indented with long narrow islands and peninsulas. The elongate configuration arises from deep glacial scour parallel to the bedrock strike. Three river estuaries enter from the north, i.e. the Kennebec, Sheepscot and Damariscotta Rivers. Bottom sediment distributions are best known from the Damariscotta River estuary (McAlice, 1977; Shipp, 1989).

The Damariscotta River is a deep narrow river estuary 29 km long. It has a small drainage basin, 780 km^2, with low river inflow, 2 m/s, and likely very low fluvial sediment input. Domestic sewage and laundry waste water is discharged locally at Damariscotta but the drainage basin overall has limited urban development and industrial activity. Dredging and disposal in the estuary are absent and thus the estuary is relatively pristine.

Configuration and bathymetry takes the form of a drowned river valley that deepens seaward to 38 m at the mouth. The longitudinal channel profile is very irregular being broken by six basins, depressions and bedrock sills. The shore is indented by numerous coves and fringed by intertidal mudflats which decrease seaward being replaced by ledges (Shipp, 1989). Marshes are scant being limited to inner coves. Mean tidal range is about 3.0 m. Although the estuary is elongate, the tripartite zonation found in other Maine systems is recognized (Smith, 1990). The inner estuarine zone with weak tides and river inflow and extensive tidal flats lies landward of Damariscotta (Fig. 8). Farther seaward is a central zone with mixed wave and tidal currents and flats interspersed between rocky headlands. Seaward of Fort Island narrows the outer zone is a shore ledge dominated due to high wave exposure.

The modern estuary is relatively young forming less than 7,500 years ago. It formed in a glacial scoured river valley which was partly filled with glaciomarine silt and clay (Shipp, 1989). As sea level rose tidal flats and marshes accumulated in coves and small tributaries; tidal currents and waves reworked old glacial deposits, scouring and depositing sediment similar to the present. Long-term submergence over the last 7,000 years proceeded at 2.8 mm/yr (Shipp, 1989) while short term rates are about 2.5 mm/yr (Gornitz and Lebedeff, 1987).

Sources

Sediment is supplied to the estuary mainly from local sources including old glacial deposits in shore bluffs augmented by reworked glacial deposits scoured from the bed (McAlice, 1977). Fluvial input from the drainage basin is likely very low because large lakes receive most drainage. However, deforestation and pasturing in historic times may have increased the input from lateral tributaries into coves. Fine sediment may be supplied from marine areas if glacial deposits on the shelf floor are resuspended by storm waves and transported into the estuary via landward estuarine flow (McAlice, 1977). Production of marshes supplies organic detritus while production of clams and oysters supplies shell (Shipp, 1989).

Pathways

Sediment within the estuary is mainly transported by tidal currents and the estuarine circulation. Tidal currents are very strong in narrow channel constrictions of the estuary with a mean flow of about 1.1 m/s (McAlice, 1977). Flood tides dominate over ebb in bottom water and thus indicative of the estuarine circulation. Pathways for fluvial material at high discharge are: 1) seaward through freshwater reaches, 2) seaward through the upper estuarine layer and downward by settling into basins, 3) landward through the lower layer to the inner salt limit just above Damariscotta. Prior to accumulation fine sediment undergoes repeated tidal cycles of settling, deposition and resuspension. This action may lead to recycling of fine sediment between channels and flats or channels and coves. As shore bluffs erode material is likely transported channelward via temporary storage in flats. Source material moves channelward in slumps (Shipp, 1989).

Sinks

The main sinks of mud accumulation are the basins and coves, their enclosed intertidal flats, especially those up estuary which is a less energetic zone for wave energy (Shipp, 1989; Smith, 1990). Rates of accumulation on tidal flats range 1.8 to 15.6 mm/yr (Smith, 1990). Constricted channels and channels near the mouth are stripped of sediment leaving much bedrock exposed.

Bottom Sediments

Muddy sediments with percentages between 40 and 80 are the most widespread type (Fig. 8). They cover the floor of basins, many intertidal flats, protected zones behind islands or bends and a few coves. A few protected coves, notably Clark Cove, have > 80% mud. Sandy sediment (< 40% mud) is distributed in small patches off points and in the channel axis just north of Clark Cove (Fig. 8). Bedrock is a common bottom type covering 16% of the floor (Shipp, 1989). Whereas mudflat shoreline dominates up estuary zones, bedrock increases seaward dominating the lower estuary shores where wave energy is intense. Bedrock outcrops on sills in narrows where strong tidal currents strip the outcrops of sediment (Shipp, 1989) (Fig. 8). The distribution of Shepard (1954) textural types is very patchy; sediments are poorly sorted, clayey to sandy silts.

Contamination Status

Pollution susceptibility of the Damariscotta River estuary ranks low due to the low population level in the drainage basin and low industrial and agriculture activity relative to estuary area. Additionally, the system is well mixed, except near the head, by strong tidal currents and thus it has good flushing ability. The summer mean flushing time is four to five weeks (McAlice, 1977).

Bottom Sediment Charts

The bottom sediments of the Damariscotta River estuary have been charted by McAlice (1977) from 42 grab samples. Additionally, Robbins (1992) occupied 21 offshore stations but the two surveys are separated by a large unsurveyed area. McAlice positioned stations by sextant bearings on landmarks. Stations are generally at 0.8 km intervals along the channel axis with some scattered along the sides or in deeper parts of coves. Laboratory analyses consisted of sieving the sand fraction and hydrometer measurements on the fine fraction. Mean size follows Folk's (1974) definition.

The distribution of mud abundance (Fig. 8) is classified into three groups and mapped by computer. The bedrock distribution is taken from Shipp (1989). This classification displays major patterns for recognizing dominant features. The chartlet was compiled using a minimum mappable unit of 0.04 km^2. Narrow transition zones of texture are not represented. Greater detail can be acquired by mapping the original data at larger scales and smaller mud class intervals. The abundance of gravel is likely under-represented by sampling because of the difficulty of collecting large material in a grab.

For sources of information and an explanation of data in the sediment inventory summary, see the text and Appendix 2.

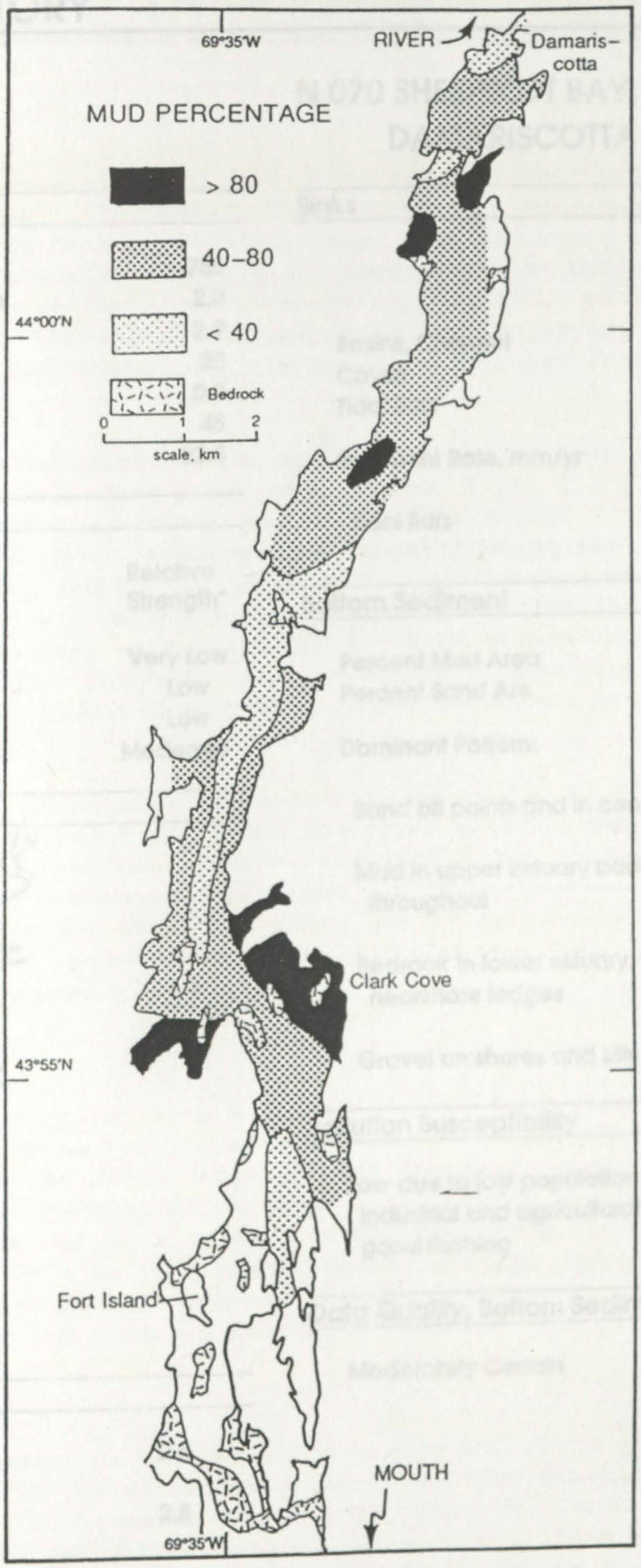


Figure 8. Distribution of mud percentage in the central and upper Damariscotta River estuary based on data of McAlice (1977).

SEDIMENT INVENTORY

N 070 SHEEPSCOT BAY, DAMARISCOTTA RIVER

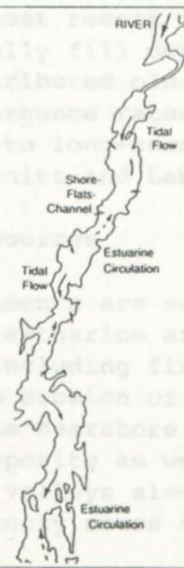
Drainage and Morphology

Total Drainage Area, Km^2	780
Average River Inflow, m^3/s	2.0
Length, Km	2.9
Average Depth, m	20
Average Width, Km	0.9
Width/Depth Ratio	45
Surface Area, Km^2	23.5

Sources

	Relative Strength*
Drainage Basin	Very Low
Older deposits, floor	Low
Production	Low
Shores, bluffs	Moderate

Pathways



Submergence Rates

Short-term mm/yr	2.5
Long-term, mm/yr (≤7,000 yrs BP.)	2.8

Sinks

	Relative Strength*
Basins, Channel	Moderate
Coves	Moderate
Tidal flats	Low to Moderate

Sediment Rate, mm/yr

Tidal flats	1.8-15.6

Bottom Sediment

Percent Mud Area	82
Percent Sand Are	14

Dominant Pattern:

Sand off points and in central estuary channel

Mud in upper estuary basins, flats and coves throughout

Bedrock in lower estuary, basin sills, nearshore ledges

Gravel on shores and sills of central estuary

Pollution Susceptibility

Low due to low population density, low industrial and agricultural activity and good flushing

Data Quality, Bottom Sediment Texture

Moderately Certain

* For total sediment

Description

Muscongus Bay consists of a rocky indented embayment with long narrow peninsulas and islands. The bedrock controls the bay configuration and bathymetry (Kelley and Belknap, 1991). These elements are partly modified by glacial scour and deposition. Population density in the drainage basin is low, less than 70 persons/km^2. Human activity, agriculture, urbanization and industry are limited. Contaminant input comes from local sources of domestic sewage at Waldoboro and Thomaston. The bay is relatively free of dredging and disposal.

The bathymetry exhibits four zones (Kelley and Belknap, 1991). 1) A river estuarine zone including reentrants, coves, tidal flats, a few marshes and narrow channels of the Medomak and St. Georges Rivers. 2) Nearshore basins are shallow (< 30 m), seaward extensions of estuaries along eroding bluffs of the mainland and behind, or adjacent to, islands or rocky shoals. 3) Shelf valleys are long narrow depressions extending seaward from the nearshore basins into deep water, i.e. 60 m. They have steep walls and smooth floors. 4) Rocky zones, which are very extensive in the bay, surround islands, shoals and peninsulas exposed to storm waves and have ridges and troughs of bedrock.

The modern bay is relatively young forming less than 7,500 years ago when the most recent rise of sea level inundated glacial scoured rock ridges and glacially fill depressions. During the rise waves and currents reworked and redistributed older deposits and these processes continue today. Short-term submergence rates are about 2.4 mm/yr (Emery and Aubrey, 1991). This contrasts to long-term submergence rates in the past 7,000 years of about 0.9 mm/yr (Gornitz and Lebedeff, 1987).

Sediment Sources

Sediments are supplied from multiple sources that vary with location. The river estuarine areas receive a small amount of fluvial input during river flooding including fines eroded from glacial deposits. Most material however, comes from erosion of glacial deposits in local bluffs (Kelley and Belknap, 1991). The nearshore basins also receive material from bluff erosion of glacial deposits as well as from reworking old glacial deposits on the floor. The shelf valleys also receive sediment, as well as shell, released from adjacent rocky zones and possibly nearshore basins.

Pathways

Sediment transport in the nearshore basins and rocky zones is driven by storm waves whereas in the river estuarine zone tides dominate. Mean tidal range is 3.0 m. In the estuarine zone tidal currents rework and redistribute fines in channels and carry them into adjacent coves, flats and marshes. Some material may be carried landward in near-bottom estuarine flow. In nearshore basin zones fine material eroded from bluffs is dispersed seaward by waves onto adjacent flats and then into basins where it is likely redistributed landward and seaward by tidal currents. Some material may eventually reach the upper parts of shelf valleys where seaward transport continues probably driven by tidal currents. Tidal currents that swept rocky zones strip sediment, prevent accumulation and carry material behind islands or into local "ponds" between outcrops (Kelley and Belknap, 1988).

Sinks

In the estuarine zone, flats, marshes, coves and reentrants are sinks for fine sediment. The main sinks for mud accumulation are the nearshore basins especially where they are protected from waves or currents by islands or shoals (Kelley and Belknap, 1991). Coarse material accumulates around rock outcrops particularly where finer material has been swept away. Mud, sand and shelly gravel fill the floor of shelf valleys (Kelley and Belknap, 1991).

Bottom Sediments

The most dominant bottom types are mud and bedrock (Fig. 9). Mud covers tidal flats and occupies coves and reentrants of the river estuarine zone where it is often mixed with gravel and shell of mussels and clams. Gravelly sand and sandy/gravel occur on the floor of narrow estuarine channels while bedrock fringes many shores and rims islands or peninsulas. Seaward of the estuaries bedrock surrounds elongate islands, peninsulas, shores and shoals, all of which trend south southwest reflecting the local metamorphic rock strike (Kelley and Belknap, 1991). Patches of boulders, gravel or sandy gravel mixed with shell hash contribute to the variability of the bedrock floor. Much of the gravel is likely glacial material left as a lag after finer material is swept away.

Mud occupies most of the nearshore basins except where narrowed and currents maintain a gravel bottom (Kelley and Belknap, 1991). Mud also occupies landward parts of shelf valley channels such as northeast of Burnt Island and west of Harbor Island. Clean sand is scarce in beaches or throughout the bay. Muddy sand or muddy gravel is found locally in reentrants or between bedrock and mud zones.

Contamination Status

The low population density relative to bay area besides low industrial, urban, chemical and agricultural activity favor low pollution susceptibility. The high tide range and fast currents promote rapid tidal flushing.

Bottom Sediment Charts

The bottom sediments of Muscongus Bay have been sampled and charted by Kelley and Belknap (1988). Within the NEI boundary of the inner bay 49 samples were collected by a Smith-MacIntyre grab. Stations were occupied on a grid at 1.0 to 1.5 km intervals. Positioning was accomplished by Loran C intersections. As noted by the workers the gravel portion is probably under-represented because of the difficulty of sampling coarse material with a grab. Laboratory analyses followed procedures of Folk (1974). Gravel size material was sieved, sand analyzed in a settling tube and mud analyzed with a Sedigraph. The grab samples, besides submersible observations, provided "ground truth" and verification for interpretation of textural patterns from side-scan sonar records and from a 3.5 kHz seismic reflection profiler.

The resulting chart of sediment texture, Figure 9, is taken from a portion of Kelley and Belknap's (1988) chart that lies within NEI boundaries. The original data were not made available for inclusion in NOAA's NEI data base. The textural patterns are assigned various patterns and keyed to the Folk triangular classification.

For sources of information and an explanation of data in the sediment inventory summary, see text and Appendix 2.

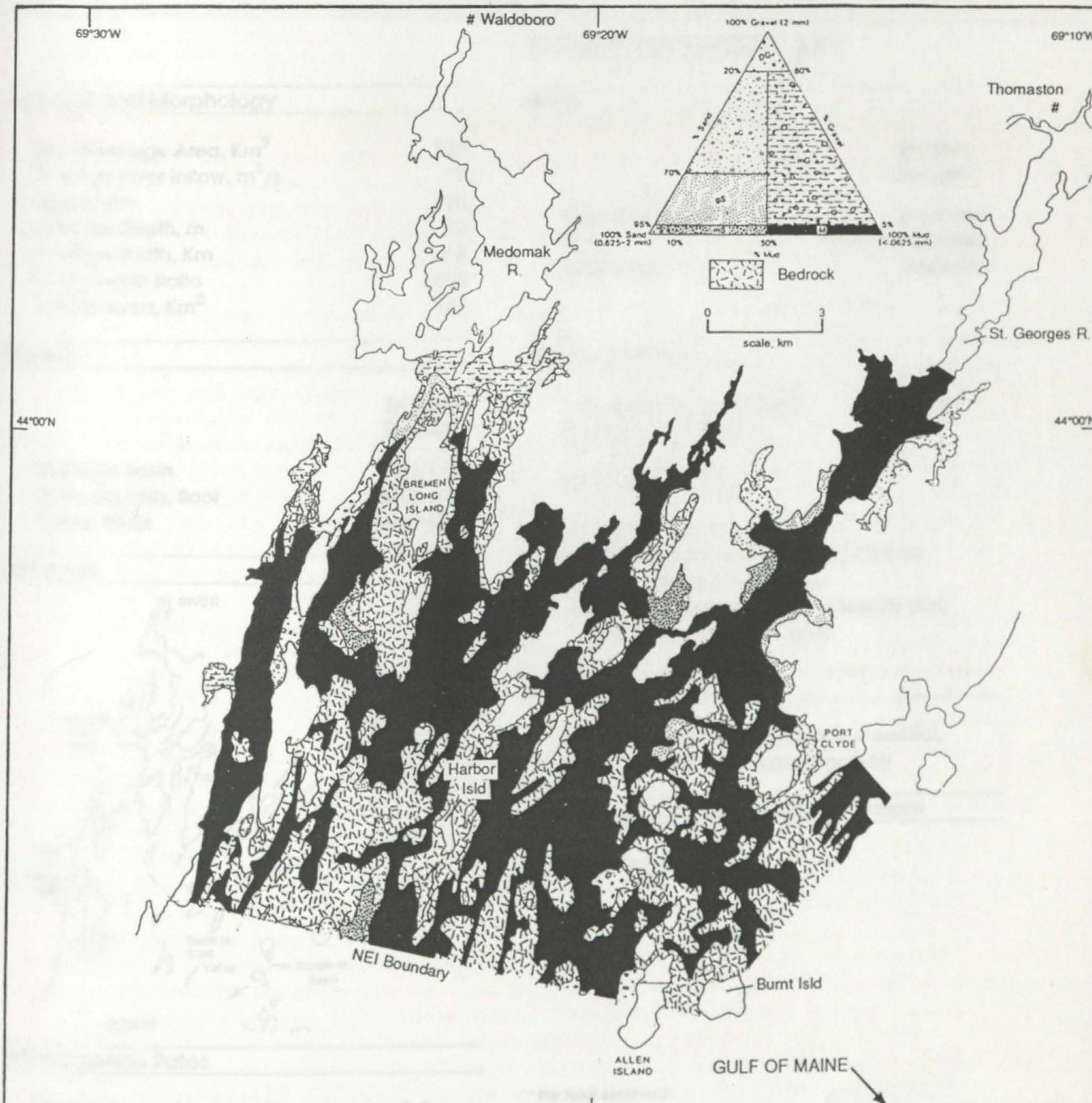


Figure 9. Distribution of sediment texture in Muscongus Bay from Kelley and Belknap (1988) and based on Folk's classification.

SEDIMENT INVENTORY

N 060 MUSCONGUS BAY

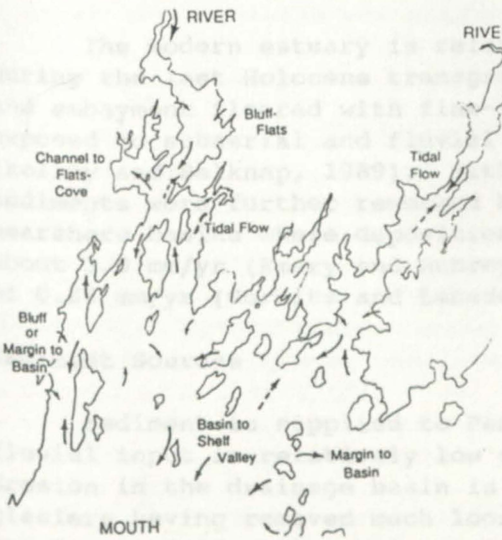
Drainage and Morphology

Total Drainage Area, Km^2	777
Average River Inflow, m^3/s	17
Length, Km	26
Average Depth, m	13
Average Width, Km	7.8
Width/Depth Ratio	600
Surface Area, Km^2	186

Sources

	Relative Strength*
Drainage Basin	Very Low
Older deposits, floor	Moderate
Shores, bluffs	Moderate

Pathways



Submergence Rates

Short-term mm/yr	2.4
Long-term, mm/yr (≤7,000 yrs BP.)	0.9

Sinks

	Relative Strength*
Nearshore basin	Moderate
Flats	Low to Moderate
Shelf valley	Moderate

Bottom Sediment

Percent Mud Area (>50%)	48
Percent Sand Area, %	-

Dominant Pattern:

Sand is scarce
Mud in nearshore basins protected by islands and in shelf valleys
Gravel in channels between islands and surrounding bedrock zones

Pollution Susceptibility

Low due to low population; low industrial, chemical, and agricultural activity

Data Quality, Bottom Sediment Texture

Fairly Certain

* For total sediment

SEDIMENT CHARACTERIZATION

Description

The Penobscot Bay is the largest major estuarine embayment along the North Atlantic coast. It covers an area of 935 km_2 and extends landward 90 km from the Gulf of Maine. Its drainage basin is mainly forested, scantly urban and agricultural. Most human activity is concentrated in ports as Bangor at the head of tide, Camden and Rockland. Dredging is limited to local harbors and disposal is localized in the central Bay. Mean tidal range if 2.9 m near the mouth and 3.9 m near the head.

The Bay floor bathymetry is quite variable. It is shaped into isolated flat floored depressions, small knolls and ridges of which some extend above water as elongate rugged islands. The Bay head up-river from Islesboro has a smooth floor and few islands. The most prominent features are three long, narrow depressions 40 to 60 m deep in the central Bay, i.e. West Passage, Middle Passage and East Passage (Fig. 10). These divide the Bay into three regions separated by chains of rounded granitic islands. Rocky zones surround the islands and these margins are littered with boulders (Kelley and Belknap, 1989). Beaches are scarce; instead the intertidal areas are dominated by tidal flats of gravel and mud derived from erosion of glacial sediments (Kelley and Belknap, 1989).

The modern estuary is relatively young forming less than 9,500 years ago during the last Holocene transgression. It formed in a glaciated river valley and embayment floored with fine-grained glaciomarine sediment which was exposed to subaerial and fluvial erosion about 11,000 to 9,500 years ago (Kelley and Belknap, 1989). With the last rise of sea level, the glaciomarine sediments were further reworked by waves and currents except in protected nearshore basins where deposition persists. Submergence proceeds today at about 3.0 mm/yr (Emery and Aubrey, 1991). This contrasts to a long-term rate of 0.85 mm/yr (Gornitz and Lebedeff, 1987).

Sediment Sources

Sediment is supplied to Penobscot Bay from multiple sources. The fluvial input is relatively low despite substantial fresh water discharge. Erosion in the drainage basin is slow because rocks are resistant, the glaciers having removed much loose soil. Eroding shores may be an important local source of sediment in areas of erodable glacier deposits. Much material, mainly fines, probably comes from glacial debris left behind on the Bay floor, especially in shoal margin zones that are reworked by waves and redistributed by currents toward, or into, the passages. Wave action is vigorous during winter months (Ostericher, 1965).

Pathways

Sediment in the Bay is transported by tidal currents and the superimposed estuarine circulation. Ebb currents at the surface, which reach 0.75 m/s off Rockland exceed flood currents. Much higher values are common in restricted channels (Ostericher, 1965). Flood currents dominate in near-bottom water especially in Middle and East passage; they are responsible for landward transport of fine sediment.

River-borne suspended sediment may be expected to follow the estuarine circulation, which is a partially mixed (Type B) regime during normal or high river discharge: 1) seaward through freshwater reaches, 2) seaward through the upper estuarine layer especially through upper west passage near Sears Island, and downward by settling especially in the upper Bay, 3) landward through the lower layer to the inner salt limit, which is between Cape Jellison and Bangor in mid-summer (Haefner, 1967). Prior to accumulation fine sediment undergoes repeated tidal cycles of settling, deposition, and resuspension. During winter months waves may become severe in exposed central areas of the Bay and likely erode and resuspend bed sediment on margins of seaward zones. Much of this is transported toward, or into, deeper water including the passages. Locally, zones of pockmarks or scour occur, notably between Sears Island and Isleboro Island (Kelley and Belknap, 1989).

Sinks

The main sink of mud accumulation is in the deep main passages west of North Haven Island (Knebel, 1986). This is formed by settling of winnowed sediments in quiet deep waters protected by islands and peninsulas. Another mud sink lies in Belfast Bay where a bathymetric depression receives river sediment via flow southward and westward from the river (Knebel, 1986). Another sink occupies the axis of East Passage.

Bottom Sediments

Mud (>80%), mainly clayey silt, is the most extensive and dominant sediment type. It fills the axes of passages as well as Belfast Bay and near-river reaches of the upper Bay (Fig. 10A). Mud is limited in seaward reaches, and locally in constricted channels where tidal currents limit accumulation. It is limited along shoal margins and around islands where it is replaced by coarse-grained sediment or gives way to bedrock. In places mud fills local depressions within bedrock zones. Mixtures of sand-silt-clay or coarse-grained sand and gravel occur near the mouth and near the head as well as close to some shores (Fig. 10B). These reflect high energy zones of wave action or near-source zones as the river, or erodable shores. The overall longitudinal pattern displays a tripartite distribution, sand-mud-sand.

Organic carbon ranges 2.7 to 13.3% being greatest near the river and in Belfast Bay, the area of a major mud sink (Larsen *et al.*, 1983). Concentrations generally diminish seaward to 0.4 or 0.7% near the north. This suggests the drainage basin is the main source of organic carbon (Larsen *et al.*, 1983).

Contamination Status

The Penobscot River is a source of industrial and sewage wastes to the Bay. Additionally, there are historic inputs of selected metals around port towns especially Searsport (Larsen *et al.*, 1983). The Bay has a moderate to high efficiency for trapping fine particles (Biggs *et al.*, 1989; NOAA, 1990). In terms of pollution susceptibility among the nation's estuaries however, Penobscot Bay ranks low because of its low population level, and low chemical, metal and agricultural activity relative to estuary area (Biggs *et al.* 1989).

Bottom Sediment Charts

The bottom sediments of Penobscot Bay within the NEI boundary have been charted from 116 core and bottom grab samples collected by Ostericher (1965). Additionally, 47 grab samples were obtained by Larsen *et al*. (1983) for analysis of percent mud, percent organic carbon and selected trace metals. Nine stations by Hathaway (1971) provide additional samples. Positioning methods are not reported. Additionally, the Bay was surveyed with a Uniboom seismic system in 1983 (Knebel, 1986) using Loran-C for navigational control, and by Kelley and Belknap (1989) also using a seismic unit besides side-scan sonar. The latter surveys delineate the thickness of Holocene sediment and boundary of subaqueous bedrock. Stations of Ostericher (1965) run along the axes of passages and across some margins at intervals of about 2 km.

The distribution of mud abundance (Fig. 10A) is classified into three groups and mapped by computer. This classification displays major patterns for recognizing dominant features. The chartlet, together with textural patterns (Fig. 10B) was compiled using a minimum mappable unit of 0.2 km^2. Because the natural distribution are highly variable and the page size scale small, not all small patches are represented. Some small mud patches of Ostericher (1965) and Larsen *et al*. (1983) fall within the bedrock zone delineated by Kelley and Belknap (1989). Greater detail can be acquired by mapping the original data at larger scales and smaller class intervals.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

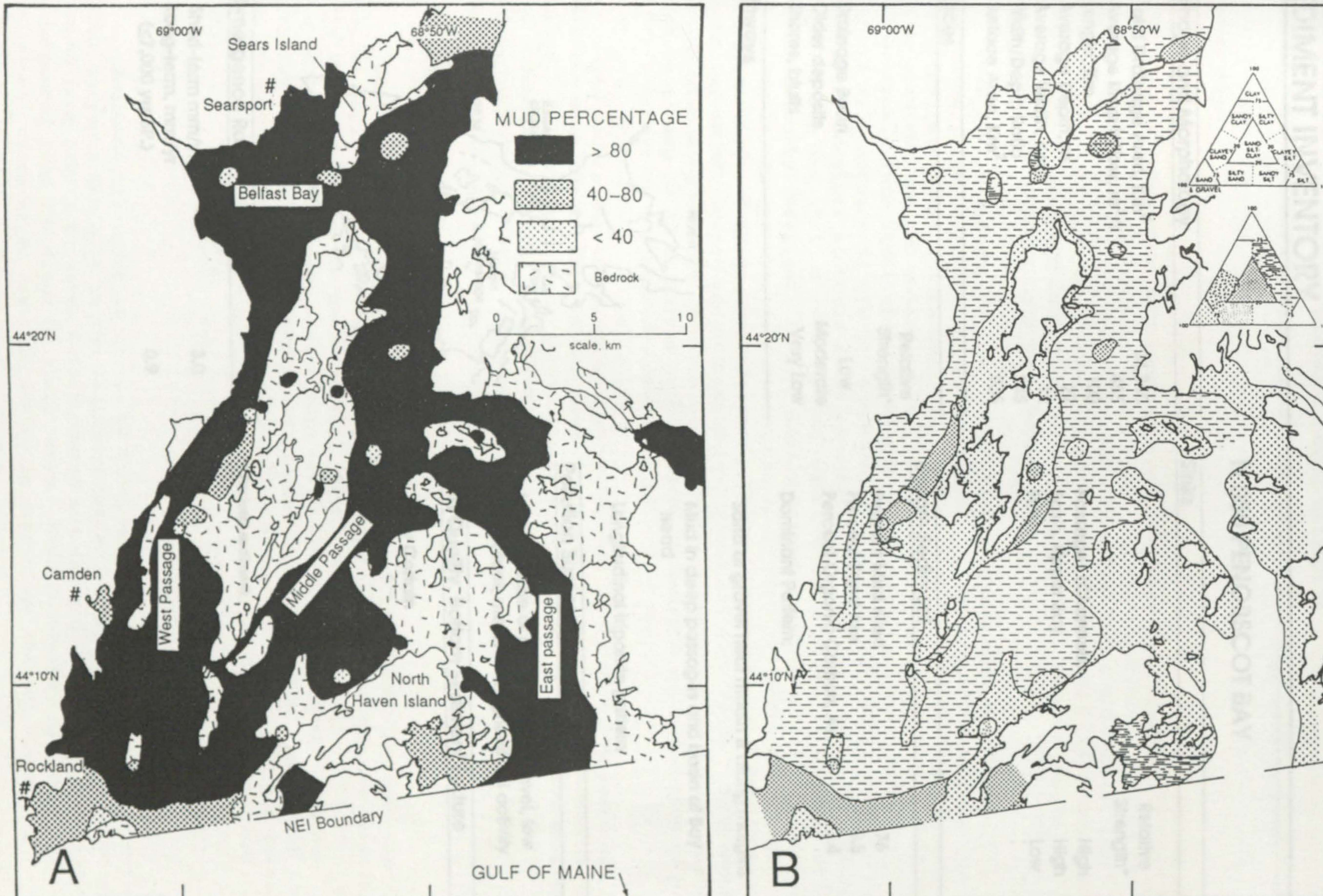


Figure 10A. Distribution of mud abundance from data of Ostericher (1965), Larsen (1983), Hathaway (1971) and bedrock distribution from Kelley and Belknap (1989).

Figure 10B. Distribution of textural types following the Shepard classification from same data sources as Figure 10A.

SEDIMENT INVENTORY

N 050 PENOBSCOT BAY

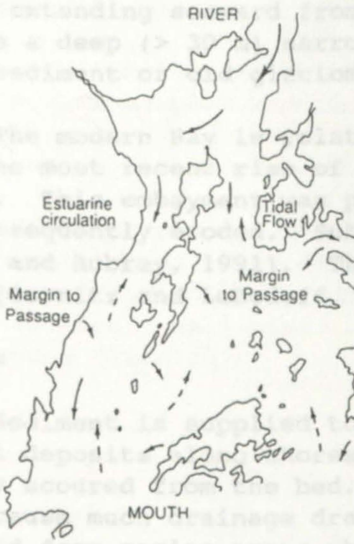
Drainage and Morphology

Total Drainage Area, Km^2	24,350
Average River Inflow, m^3/s	455
Length, Km	100
Average Depth, m	22
Average Width, Km	12
Width/Depth Ratio	545
Surface Area, Km^2	935

Sources

	Relative Strength*
Drainage Basin	Low
Older deposits	Moderate
Shores, bluffs	Very Low

Pathways



Submergence Rates

Short-term mm/yr	3.0
Long-term, mm/yr (≤7,000 yrs BP.)	0.9

Sinks

	Relative Strength*
Passages (Channels)	High
Basin, Upper Bay	High
Flats	Low

Bottom Sediment

Percent Mud Area	76
Percent Sand Are	0.5
Percent Organic Carbon, Av.	2.4

Dominant Pattern:

Sand or gravel near mouth & along margins

Mud in deep passages and basin at Bay head

Longitudinal tripartite pattern

Pollution Susceptibility

Low because of low population level, low chemical, metal and agricultural activity

Data Quality, Bottom Sediment Texture

Fairly Certain

* For total sediment

SEDIMENT CHARACTERIZATION

N040 BLUE HILL BAY

Description

Blue Hill is a large (1150 km^2) deep bay that is an important component of the large island-bay complex on the central Maine coast (Barnhardt and Kelley, 1991). Human activity, agriculture and urbanization is limited and the population density is low, less than 72 persons/km^2. Contaminant input consists of local sources of domestic sewage discharged into the Union River at Ellsworth. Dredging is limited to a shallow channel through the Union River mouth and another into Bass Harbor.

The Bay is elongate-shaped and protected by numerous islands and peninsulas. The configuration and bathymetry is determined by bedrock structure (Barnhardt and Kelley, 1991). Metamorphic rocks rim the shoreline while granite rims the islands. Sand and gravel beaches are scant and of the pocket type. Intertidal tidal flats are mixed gravel and mud substrates derived from erosion of glacial shore deposits (Barnhardt, 1992). The bathymetry consists of three zones (Barnhardt and Kelley, 1991): 1) nearshore basins which are shallow (< 50 m) low relief zones adjacent to the mainland and bordered by intertidal flats. This embraces upper Blue Hill Bay landward of Tinker Island and shallow parts of the lower bay. 2) Rocky zones with extreme relief and large boulder zones. These surround most islands in the lower bay as Mt. Desert and between Swans Island and Flye Point. 3) A shelf valley extending seaward from the nearshore basin northeast of Swan's Island. This is a deep (> 30 m) narrow zone bordered by bedrock walls and floored with muddy sediment or old glaciomarine material.

The modern Bay is relatively young forming less than 6,500 years ago when the most recent rise of sea level inundated a glacial scoured embayment valley. This embayment was partly filled with reworked glaciomarine sediments and subsequently eroded. Submergence continues today at about 2.6 mm/yr (Emery and Aubrey, 1991). This contrasts to long-term, 7,000 year rate of 0.9 mm/yr (Gornitz and Lebedeff, 1987).

Sources

Sediment is supplied to the bay mainly from local sources, i.e. old glacial deposits along shores by wave erosion, besides glaciomarine material locally scoured from the bed. Fluvial input from the drainage basin is likely low because much drainage drains into large lakes. Fine sediment may be supplied from marine areas where old glacial deposits on the inner shelf floor are resuspended by storm waves. Production of barnacles, urchins and mussels in rocky zones supplies significant amounts of shell fragments (Barnhardt, 1992).

Pathways

Sediment transport is driven by tidal currents augmented by wave action. Tidal currents dominate in the nearshore basins. They redistribute material eroded from bluffs by waves both landward and seaward, as well as material resuspended from the floor by storm waves. Tidal currents together with occasional storm waves are also active in near-river reaches where they redistribute and exchange bluff or fluvial material between flats, coves, rocky zones and the basins. In the outer shelf valley zone tidal currents transport material from nearshore basins and rocky zones to deeper water. Some material is also transported by slumping (Barnhardt and Kelley, 1991).

Sinks

In near-river reaches, shoals, flats and coves are the main sinks of fine sediment. In the upper bay and nearshore basin zone, material accumulates irregularly on the basin floor particularly adjacent to rocky zones where sediment is stripped from bedrock. For another part material eroded from bluffs accumulates in mudflats or sandflats which may be temporary storage sites. In seaward areas, coarse material accumulates in pocket beaches and on the shelf valley floor.

Bottom Sediments

Mud is a dominant bottom type. Mud with percentages ranging 40 to 60 percent covers the floor of nearshore basins in the upper and lower bay (Fig. 11). Additionally, it occurs in reentrants and large coves and bordering intertidal flats. In contrast, gravel with low mud percentages (< 40%) is distributed in rocky zones on shoals around islands, e.g. Mt. Desert, Tinker, and between Swans Island and Naskeag Point, off exposed headlands as at Blue Hill and the south shore of Long Island. Additionally, gravel is found on the shelf valley floor northeast of Swans Island. Bedrock is exposed along shores and nearshore shoals especially in seaward areas of the bay as Swans and islands to the northeast (Fig. 11).

Organic matter ranges 2.5 to 6.6% and averages 4.1% being higher in clay and silt rich samples than in others.

Contamination Status

Pollution susceptibility of Blue Hill Bay is relatively low because of its low population level in the drainage basin, and its low industrial, chemical and agricultural activity relative to bay area. Additionally, the system is likely well mixed except near the river by tidal currents and thus it has good flushing,

Bottom Sediment Charts

Bottom sediments of Blue Hill Bay have been charted by Barnhardt and Kelley (1991) and by Barnhardt (1992). In these surveys ten stations were occupied and grab samples collected as "ground truth" for side scan sonar records and for seismic reflection profiles. Loran C navigation provided positions for grabs and track lines. The ten stations within NEI boundaries of the lower bay are widely spaced at about 3 km intervals. Laboratory analyses consisted of sieving gravel, settling tube for sand and pipette for silt and clay. To generate Figure 11 the data on mud percentages from ten stations, which were mapped by computer, was integrated with the distribution of surficial sediments charted by Barnhardt and Kelley (1991) utilizing the Folk classification. The bedrock distribution is also taken from Barnhardt and Kelley (1991) and based on side scan sonar and seismic surveys.

For sources of information and an explanation of data in the sediment inventory summary, see text and Appendix 2.

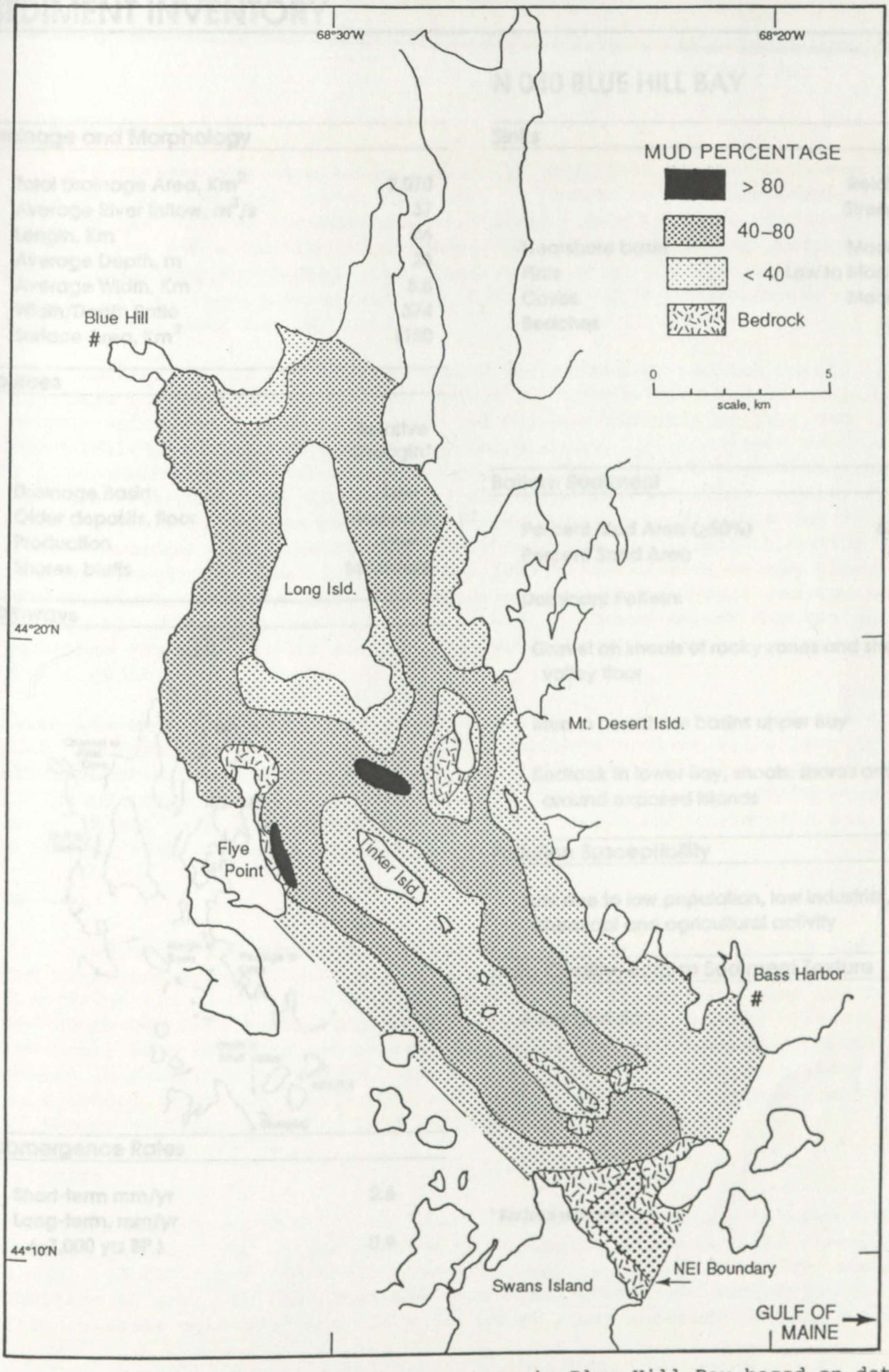


Figure 11. Distribution of mud percentage in Blue Hill Bay based on data from Barnhardt (1992) and Barnhardt and Kelley (1991).

SEDIMENT INVENTORY

N 040 BLUE HILL BAY

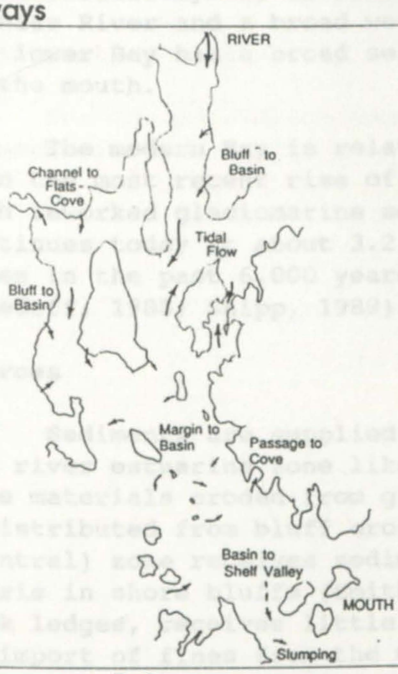
Drainage and Morphology

Total Drainage Area, Km^2	2,070
Average River Inflow, m^3/s	37
Length, Km	46
Average Depth, m	23
Average Width, Km	8.6
Width/Depth Ratio	374
Surface Area, Km^2	1150

Sources

	Relative Strength*
Drainage Basin	Low
Older deposits, floor	Moderate
Production	Low
Shores, bluffs	Moderate

Pathways



Submergence Rates

Short-term mm/yr	2.6
Long-term, mm/yr (≤7,000 yrs BP.)	0.9

Sinks

	Relative Strength*
Nearshore basin	Moderate
Flats	Low to Moderate
Coves	Moderate
Beaches	Low

Bottom Sediment

Percent Mud Area (≥50%)	62
Percent Sand Area	-

Dominant Pattern:

Gravel on shoals of rocky zones and shelf valley floor

Mud in nearshore basins upper Bay

Bedrock in lower Bay, shoals, shores and around exposed islands

Pollution Susceptibility

Low due to low population, low industrial, chemical and agricultural activity

Data Quality, Bottom Sediment Texture

Fairly Certain

* For total sediment

N020 ENGLISHMAN BAY, MACHIAS BAY

Description

Englishman Bay is a rugged, sparsely populated coastal embayment that typifies the "downeast" coast of Maine. It contains two subembayments of which Machias Bay is the easternmost. Human activity, i.e., industry, agriculture, and urbanization is very limited, fishing being predominant. The only contaminant input comes from local sources of domestic sewage, canneries, and fabrics at the towns of Machias, East Machias, and Machiasport on the Machias River near the bay head.

Machias Bay is rectangular-shaped determined by bedrock faults. It is separated into an upper and lower sector by Sprague Neck and several mid-Bay islands which are topped by glacial end moraine and thin drift. The intertidal geomorphology consists of three zones: 1) the lower Bay dominated by high energy waves with abundant ledges and occasional pocket beaches; 2) the upper (central) Bay dominated by mixed energy conditions, waves, and currents, with extensive mud or sandflats fronting eroding bluffs; 3) the river estuarine zone dominated by tidal currents with mudflats backed by marshes fronting stable bluffs (Shipp, 1989). Bathymetry of the upper Bay is characterized by two distinct channels, a narrow deep branch leading into the Machias River and a broad west branch leading toward Holmes Bay (Shipp, 1989). The lower Bay has a broad seaward sloping floor which deepens abruptly to 48 m at the mouth.

The modern Bay is relatively young forming less than 6,500 years ago when the most recent rise of sea level inundated a river valley partly filled with reworked glaciomarine sediments and subsequently eroded. Submergence continues today at about 3.2 mm/yr (Emery and Aubrey, 1991) while long-term rates in the past 6,000 years are about 0.5 to 1.5 mm/yr (Gornitz and Lebedeff, 1988; Shipp, 1989).

Sources

Sediments are supplied from multiple sources that vary with location. The river estuarine zone likely receives a small fluvial input which includes fine materials eroded from glacial deposits. Additionally, some sediment is redistributed from bluff erosion in the upper (central) zone. The upper (central) zone receives sediment episodically by wave erosion of glacial debris in shore bluffs (Smith, 1990). The lower zone, which is flanked by rock ledges, receives little sediment except for pocket beaches. Some degree of import of fines from the Gulf of Maine is possible.

Pathways

Sediment transport in the lower zone is driven mainly by wave action whereas in the river estuarine zone tides dominate. Mean tidal range is 3.8 m. In the upper (central) zone mixed energy, waves and tides, dominate in addition to ice. In the estuarine zone tides rework and redistribute fines from channels onto adjacent flats and marshes and material is likely recycled to the channel as well. Some sediment may escape seaward to the upper (central) Bay. In the upper (central) Bay transport of coarser and fine material is mainly from bluffs to flats to channel with exchange landward or seaward into adjacent zones. Some material is likely transported by slumping (Shipp, 1989). In the lower zone transport may be either seaward or landward or into adjacent pocket beaches.

Sinks

In the estuarine zone, flats and marshes are the main sinks (Smith, 1990; Shipp, 1989). In the upper (central) zone intertidal sand or mud flats fronting eroding bluffs are the chief sinks (though temporary) while much material accumulates on the channel floor. In the lower zone, pocket beaches and spits are sinks for coarse material.

Bottom Types

Bedrock is a dominant bottom type. Its distribution (Figure 12) generally increases seaward where it fringes islands exposed to wave attack. In contrast, sand and mud flats generally increase landward with mud being dominant in Holmes Bay and in the Machias River mouth vicinity. No bottom sediments have been collected on the floor but side-scan sonar shows an overall-fining trend from the mouth to the head (Shipp, 1989). Sandy mud and muddy sand are the dominant sediment types with sand and gravel predominant locally in the central Bay where moraines are eroding.

Contamination Status

The low population density, scant human activity, and rapid tidal exchange favor relatively low pollution susceptibility.

Bottom Sediment Charts

The distribution of bedrock (Figure 12) has been charted by Shipp (1989) from 333 km of seismic reflection tracks that crisscross the Bay on more than 27 lines. The bedrock surface is delineated where sediment is less than 1.0 m thick (Shipp, 1989). The distribution of mudflats and sandflats is taken from Timson (1977) and Smith (1990). No textual analyses on Bay sediments are available.

For sources of information and explanation of data in the "sediment inventory", see text, Appendix 2 or the original sources (Smith, 1990; Shipp, 1989).

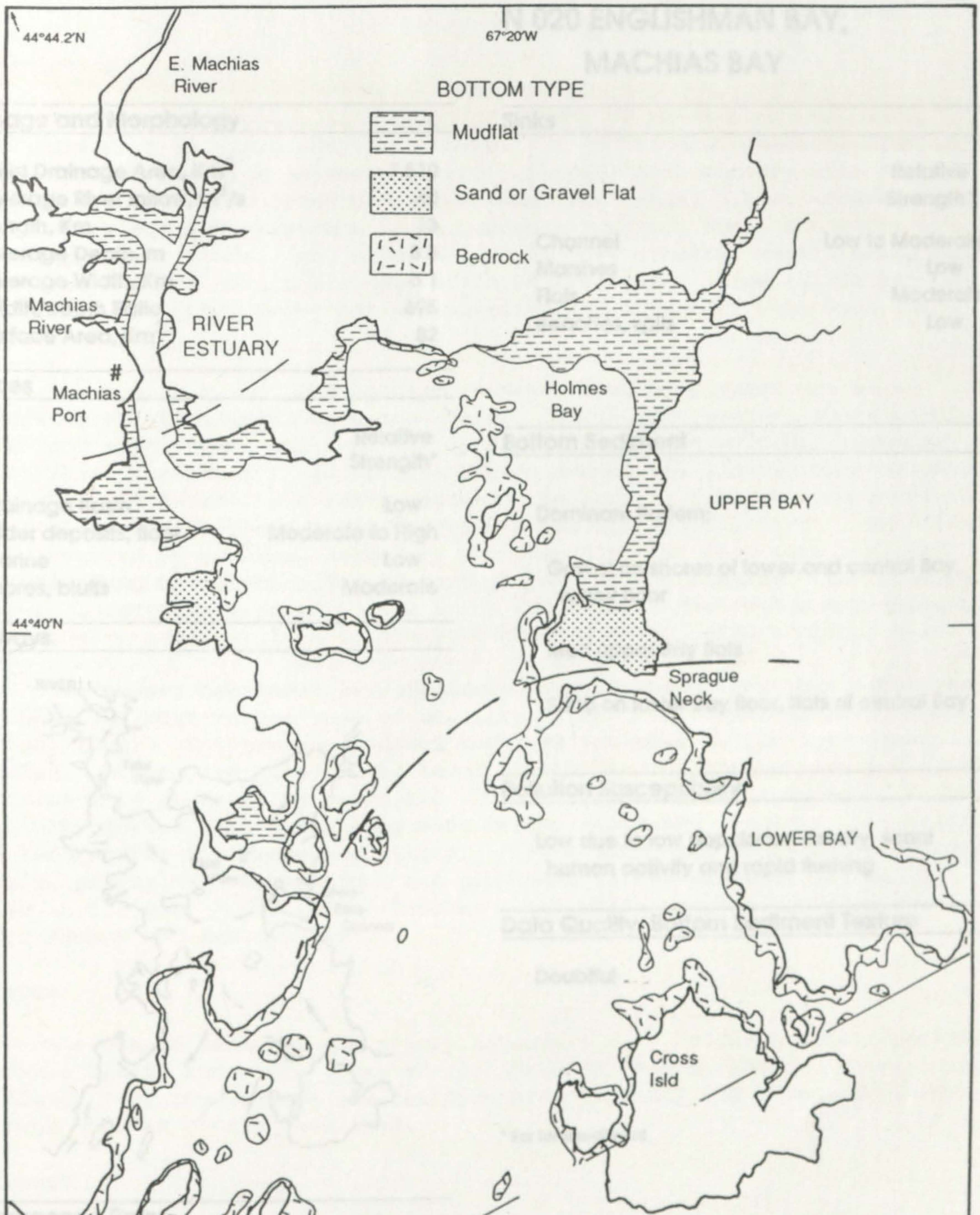


Figure 12. Distribution of bedrock from Shipp (1989) and of mudflats and sandflats from Tinson (1977) and Smith (1990).

SEDIMENT INVENTORY

N 020 ENGLISHMAN BAY, MACHIAS BAY

Drainage and Morphology

Total Drainage Area, Km^2	7,510
Average River Inflow, m^3/s	40
Length, Km	13
Average Depth, m	8.8
Average Width, Km	6.1
Width/Depth Ratio	695
Surface Area, Km^2	82

Sources

	Relative Strength*
Drainage Basin	Low
Older deposits, floor	Moderate to High
Marine	Low
Shores, bluffs	Moderate

Pathways

Submergence Rates

Short-term mm/yr	3.2
Long-term, mm/yr ($\leq$6,000 yrs BP.)	0.5-1.5

Sinks

	Relative Strength*
Channel	Low to Moderate
Marshes	Low
Flats	Moderate
Beaches, spits	Low

Bottom Sediment

Dominant Pattern:

Gravel on shores of lower and central Bay, valley floor

Mud upper Bay flats

Sand on lower Bay floor, flats of central Bay

Pollution Susceptibility

Low due to low population density, scant human activity and rapid flushing

Data Quality, Bottom Sediment Texture

Doubtful

* For total sediment

SEDIMENT CHARACTERIZATION

N010 PASSAMAQUODDY BAY, LUBEC EMBAYMENT

Description

The Lubec Embayment is a small (2.7 km^2) re-entrant in the south, seaward end of Passamaquoddy Bay, Maine. It is the easternmost system in the United States and lies adjacent to the international boundary with Canada. The system is distinguished by its extreme tide range, 5.7 m. Consequently, tidal flats are extensive and tidal currents strong. Human activity, i.e., industry, agricultural, and urbanization is very limited, shellfishing being predominant. The entire drainage basin is relatively large (8,300 km^2) but streams in the Lubec Embayment are sluggish and irregular with bogs and marshes common.

The configuration and bathymetry are shaped by current and wave reworking of old glacial deposits (Walsh, 1988). The western shore consists of a long spit, Lubec Spit, backed by a salt marsh cut by tidal channels. The south shore consists of low eroding bluffs and on the eastern end, by Quoddy Spit which is backed by a small lagoon. The central embayment consists of tidal flats with topography up to 4.5 m above MLW (Walsh, 1988). The flats are dissected by numerous secondary ebb channels that lead into a master channel along the south side and through central Lubec Marsh. Two prominent bedrock ledges are exposed in the north and central part while a prominent intertidal gravel bar (the Causeway) links the north ledge to Lubec Spit.

The modern embayment is relatively young forming less than 4,000 years ago when the most recent rise of sea level inundated former glacial deposits (Walsh, 1988). The present bedrock form was sculpted by previous glacial erosion. During the rise of sea level Pleistocene glacial marine and earlier deposits were reworked by waves and tidal currents. The Lubec Spit, which initially formed across the embayment mouth, retreated landward, disintegrated and reformed at its present position. Bluffs along the south shore receded as erosion prevailed. Submergence has proceeded in the range of 1.0 to 11.5 mm/yr in the past 3,000 years (Timson, 1978) while short-term rates are 3.7 mm/yr (Emery and Aubrey, 1991).

Sources

Sources of sediment are mainly internal, i.e., older glacial deposits in erodable bluffs and along tidal channel margins (Walsh, 1988). Fluvial input is likely very low because the drainage area is small and stream drainage through bogs is poorly developed.

Pathways

Sediment transport is driven mainly by tidal currents augmented by wave action at high tide and by ice rafting (Walsh, 1988). Tidal currents are mainly ebb dominated throughout the embayment reaching 50 cm/s in the inlet channel off Lubec Spit. Velocities are lower (< 20 cm/s) and variable on the intertidal flats (Walsh, 1988). Despite ebb dominance, sediment transport indicated by bedforms, algal fronds and seaweed clasts (Walsh, 1988) is predominately landward except at the inlet delta. This reflects augmentation by waves. Landward movement of intertidal swash bars is effective in accretion of Lubec and Quoddy Spits (Walsh, 1988).

Sinks

The main sinks for sand and gravel sediment are the spits and central intertidal flats. A small sink of sand occurs in the ebb tidal delta. Mud accumulates in the lagoon behind Quoddy Spit, in salt marshes and also in south central reaches where it is mixed with sand. Sedimentation rates on the flats range 4 to 8 mm/yr (Walsh, 1988) increasing toward the Causeway. Erosion occurs along the seaward edge of the embayment and along the south bluffs.

Bottom Sediments

Sand and sandy gravel/gravelly sand are the dominant textural types with mud significant only in back-spit environments, or where Pleistocene mud is exposed by scour in the central flats (Walsh, 1988). Sand is abundant on the intertidal flats especially in the lower intertidal zone of seaward areas (Figure 12). It is typically well-sorted and fine to medium size. Sandy gravel/gravelly sand covers the mid-intertidal zone and the inlet besides some swash bars. Gravel/sandy gravel form most of Lubec and Quoddy Spits.

Contamination Status

Pollution susceptibility of the Lubec Embayment is relatively low because of its small drainage basin with a low population density and low human activity. The high tidal range and fast currents promote high tidal flushing ability.

Bottom Sediment Charts

The bottom sediments of the Lubec Embayment have been charted by Walsh (1988) from 37 cores distributed in zones of different geomorphic/ sedimentologic character. Sampling design, complete station locations and positioning techniques are not reported. Laboratory analyses follow techniques of Folk (1974) with dry and wet sieving of coarse fractions and pipetting of the fine fraction. The resulting textural data are classified by the Folk triangular classification as presented by Walsh (1988) (Figure 13).

For sources of information and exploration of data in the sediment inventory, see text, Appendix 2 or the original source Walsh (1988).

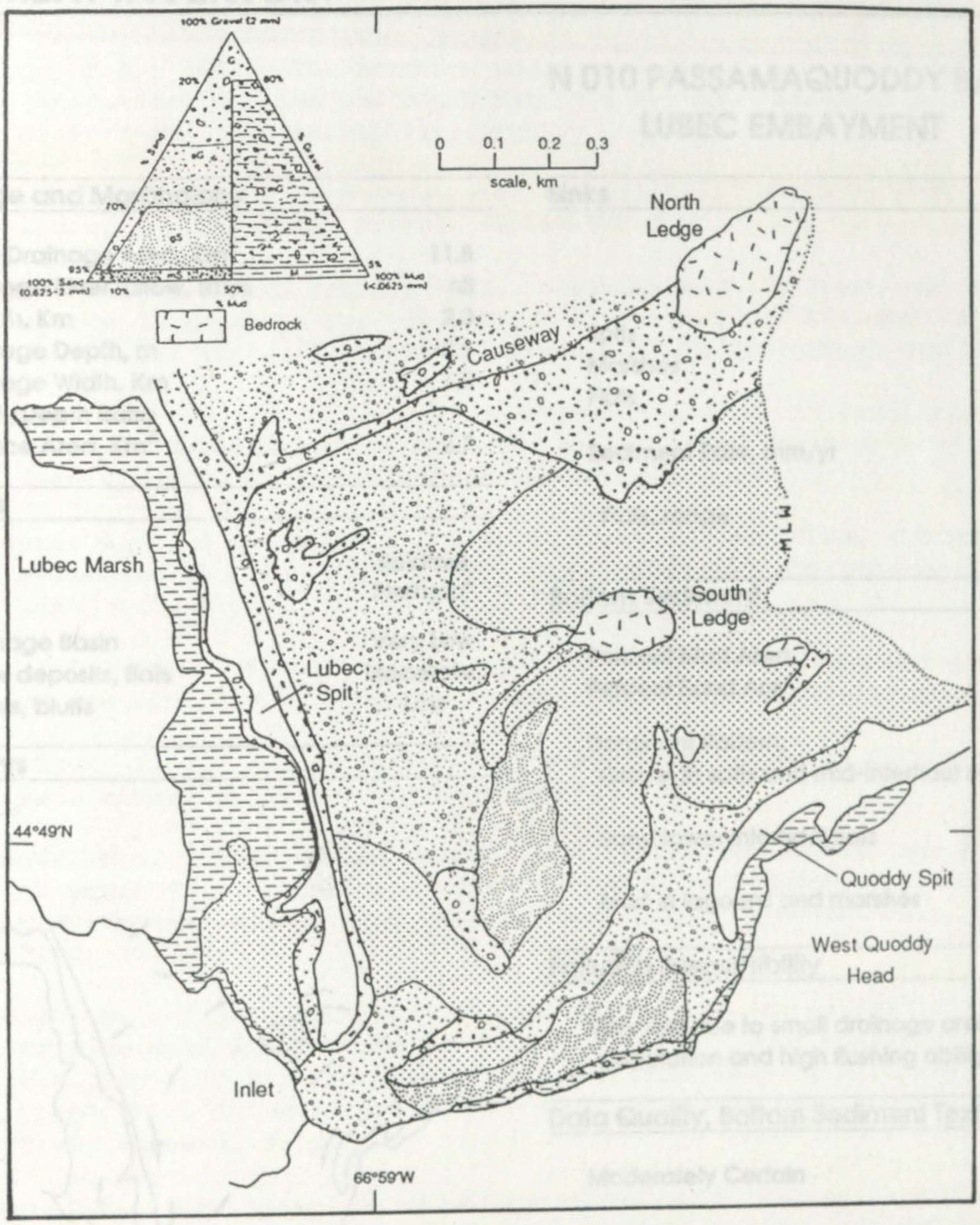


Figure 13. Distribution of bottom sediment types following Folk classification, triangle; after Walsh (1988).

SEDIMENT INVENTORY

N 010 PASSAMAQUODDY BAY, LUBEC EMBAYMENT

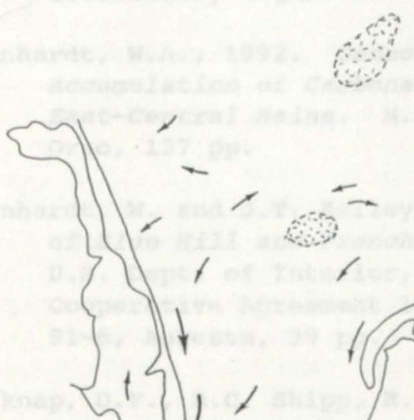
Drainage and Morphology

Total Drainage Area, Km^2	11.8
Average River Inflow, m^3/s	nil
Length, Km	2.0
Average Depth, m	-0.9
Average Width, Km	1.2
Width/Depth Ratio	
Surface Area, Km^2	2.7

Sources

	Relative Strength*
Drainage Basin	Very Low
Older deposits, flats	Moderate
Shores, bluffs	Low

Pathways



Submergence Rates

Short-term mm/yr	3.7
Long-term, mm/yr (≤3,000 yrs BP.)	1.0-11.5

Sinks

	Relative Strength*
Spits	High
Marshes	Low
Flats	Moderate

Sediment Rate, mm/yr

Flats, range	4 to 8

Bottom Sediment

Percent Mud Area	7
Percent Sand Are	-

Dominant Pattern:
Gravel in spits and mid-intertidal flats

Sand lower intertidal flats

Mud in lagoons and marshes

Pollution Susceptibility

Very low due to small drainage area, low population and high flushing ability.

Data Quality, Bottom Sediment Texture

Moderately Certain

* For total sediment

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Appendix 1

Table 1. Organization of data quality and criteria used for assessment of scientific certainty of data in the database.

1. DATA SOURCE QUALITY

(1) Data Forms

Data produced by laboratory analysis of sediment texture (e.g. wet-sieving, pipetting, hydrometer and settling tube analysis, etc.) is considered the highest quality. Numeric values (e.g. tables, computer files) are considered to produce a better data set than isopleths or charted distributions. NOS bottom notations or field descriptions are considered the lowest quality.

	Weight
A. Laboratory Processed	
- Available as measured values	3
- Available as isopleths or charted distributions	2
B. Non-Laboratory Processed	
- NOS bottom notations or visual description	1

(2) Degree of Laboratory Processing

Laboratory processed data in terms of percent sand-silt-clay, which enables Shepard's classification of sediment texture, has priority over statistical parameters (e.g. mean, median, mode, sorting, etc.). The percent mud or sand/mud ratio, which is usually measured by wet sieving, is also considered to have lower quality than percent sand-silt-clay.

A. Percent Sand-Silt-Clay	2
B. Percent Mud, Mean, or Median	1

(3) Documentation

Published data that has been peer-reviewed is regarded highly certain. Semi-published "grey" literature, including technical reports, theses, or dissertations are not peer-reviewed and regarded as lesser quality.

A. Published	3
B. Semi-published "Grey" Literature, Tech. Reports, Theses, or Dissertation	2
C. Unpublished Field Data	1

(4) Spatial Sampling Density

Sampling density is determined by the number of stations per 10 km^2. This is the most important factor affecting source data quality. The critical values of 1,3,5, and 7 are set by testing the data for the Chesapeake Bay and its tributaries.

A.	> 7 stations / 10 km^2	5
B.	5 - 7 stations / 10 km^2	4
C.	3 - 5 stations / 10 km^2	3
D.	1 - 3 stations / 10 km^2	2
E.	< 1 stations / 10 km^2	1

(5) Additional Parameters other than texture

The textural parameters are often interrelated to other measured parameters (e.g. organic content, water content, etc.). Whenever these additional parameters are measured and abundant, the data quality is more assured.

A. Available other parameters 1

The data source quality weightings are normalized by dividing by 15 (the maximum number of points) and scaled to 100%.

2. MAPPABILITY

(1) Sampling Density

When several sets of source data are used to map an estuary, the sampling density in terms of the whole estuary is important to decide the mappability. The values of 3 and 7 stations/10 km^2 are set by testing the data for the Chesapeake Bay and its tributaries.

		Weight
A.	> 7 stations / 10 km^2	3
B.	3 - 7 stations / 10 km^2	2
C.	< 3 stations / 10 km^2	1

(2) Spatial Coverage

The end product of the computer processing is a chart that shows the distribution of values by parameter from one or several data sources. The coverage in terms of percent of the whole estuary is used to assure the certainty of data representation.

A. > 80 %	3
B. 60 - 80 %	2
C. < 60 %	1

(3) Consistency, Number and Compatibility of data sets

Variations of different data sources in time and space are important in producing consistent composite charts. The best chart consists of a single data source that covers the whole estuary at one time. The smaller is the number of data sources in a composite, the better the mappability.

A. 1 - 2	3
B. 3 - 4	2
C. > 4	1

(4) Temporal Coverage

Multiple coverage of the same area at several times strengthens the reliability of a chart.

A. Over two data sets	2
B. Less than two data sets	1

(5) Additional Parameters other than texture

The distribution of additional parameters strengthens the reliability of a chart since many parameters are interrelated to grain size.

A. Other parameters available	1

The data mappability weightings are normalized by dividing by 12 (the maximum number of points) and scaled to 100%.

3. AGGREGATE QUALITY

Normalized weightings of all data source quality values and mappability values are then averaged and assigned descriptors.

(1) > 85	Highly Certain	-	Excellent Data Set and Mappability
(2) 71 - 85	Moderately Certain	-	Good Data Set and Mappability
(3) 56 - 70	Fairly Certain	-	Fair Data Set and Fair Mappability
(4) 40 - 55	Reasonable Inference	-	Fair Data Set and Reasonable Mappability
(5) < 40	Doubtful	-	Rejected Data Set

Appendix 2

KEY TO SEDIMENT INVENTORY SHEETS

Code Number is a NOAA code to identify estuary systems included in the National Estuarine Inventory (NEI). M numbers are for systems in the Middle Atlantic region.

Drainage and Morphology give the fundamental hydrologic and morphologic data from NOAA, 1990; drainage area embraces the total drainage area including the estuarine drainage area and the fluvial drainage area; river (stream) inflow is the annual average inflow for the entire system; width is the average width; depth the average depth for the entire system; depth/width ratio is the ratio of estuary depth to width; sinuosity of river estuaries is the ratio of channel length to valley length.

Sources are the sediment sources for either: 1) the total sediment input, e.g. mud, sand and biogenic material, or 2) the total fine sediment, e.g. mud or silt plus clay. Where input rates are known such as part of a mass balance, the strength is expressed as a percentage of the whole. Where rates of input are not measured the source is reported qualitatively according to its relative strength in the system; very low is 0 - 10%; low is 11 - 30%; moderate is 31 to 70%; high is 71 to 100%.

Pathways are the likely routes of sediment transport from the source to the sink, or loss by export, displayed in plan view. Bold arrow represents relatively strong transport; thin arrow, weak transport. Near-bottom transport, dashed arrow; near-surface, solid.

Submergence Rates are the rates of relative land (sea) level change either short-term based on tide gages over periods of 20 to 80 years, or long-term, geologic trends in the last 4,000 years.

Sinks are sediment accumulation zones in the estuary for either: 1) total sediment, or 2) fine sediment. Where accumulation rates are known such as part of a mass balance, the strength is expressed as a percentage of the whole. Where measured rates are not available the sink is reported qualitatively according to its relative strength; very low is 0 - 10%; low is 11 - 30%; moderate is 31 to 70%; high is 71 to 100%.

Mass Balance is a sediment budget for either: 1) total sediment, or 2) fine sediment, in which the sources (inputs) are balanced by the losses, i.e. into the sinks or through export to the ocean. Data come mainly from the published literature reported in the characterization reports. Two or more balances reflect a range of estimates from different data sources and in turn, different methodology or data uncertainties.

Storage Efficiency is the ability of an estuary to retain and accumulate fine sediment delivered to it. This is expressed as a ratio of the accumulation rate in all sinks to the drainage basin input rate. The rates come from the mass balance. A ratio of one implies the amount of sediment is equivalent to the amount supplied by the drainage basin. A ratio greater than one implies the estuary stores more sediment than is supplied by its drainage basin.

Bottom Sediments

Mud Area is the percentage of the total estuary area occupied by mud > 40%. In systems lacking mud > 40%, an alternate percentage or class is substituted as indicated.

Sand Area is the percentage of the total NEI estuary (surface) area > 60% sand.

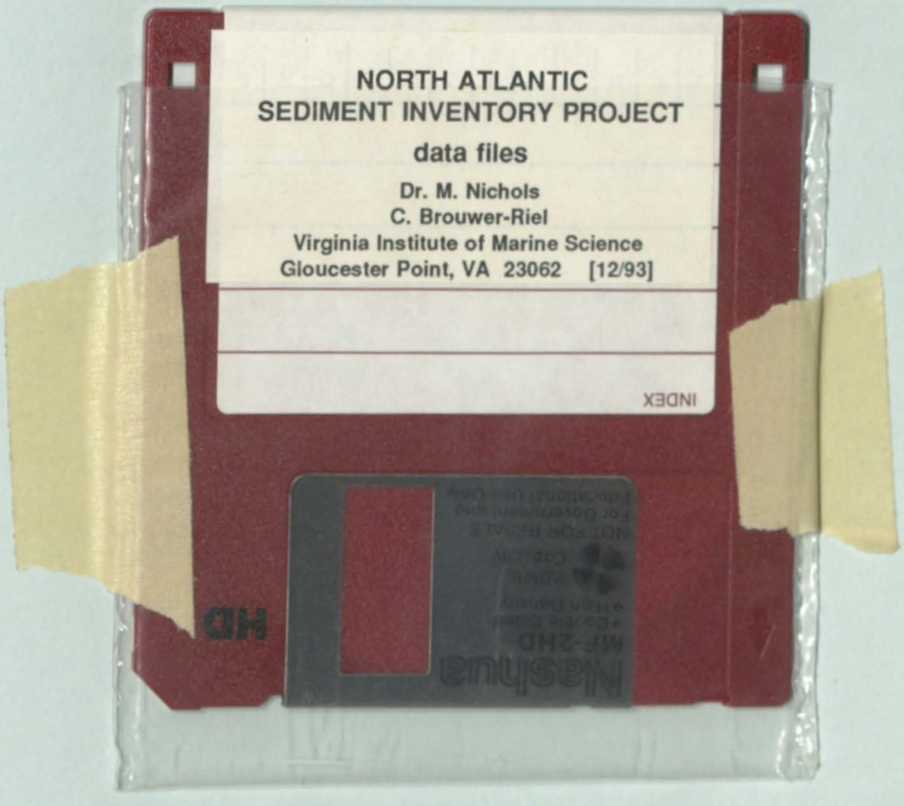
Water Content is the mean percentage water content expressed as wet weight (0 to 100%).

Organic Matter is the mean percentage organic matter. Where original source data are expressed as organic carbon, the carbon values were multiplied by a factor of 1.8 to obtain organic matter values.

Pattern is the gross distribution of sand and mud, i.e. longitudinally along the channel from head to mouth or laterally across the middle or lower portion of the system. In some systems the dominant pattern is described according to morphologic features.

Pollution Susceptibility is the relative pollution potential of the system as determined by 1) hydraulic characteristics, i.e. ability of the system to flush dissolved pollutants, and 2) exposure to anthropogenic activities in the drainage basin. Relative rankings are from Biggs *et al.* (1989) and based on comparison of 78 U.S. estuaries. For further explanation see text.

Data Quality is the overall relative quality including the quality of the data source(s) and the mappability of combined sources. Rankings range "highly certain," "moderately certain," "fairly certain," "reasonable inference" and "doubtful." For details see Appendix 1.


NORTH ATLANTIC
SEDIMENT INVENTORY PROJECT
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